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SPRINKLER PERFORMANCE IN RESIDENTIAL FIRE TESTS

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SPRINKLER PERFORMANCE IN RESIDENTIAL FIRE TESTS

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ABSTRACT

Sprinkler performance as affected by sprinkler link sensitivity, link temperature rating, and water distribution has been investigated in several typical flame-initiated residential fire scenarios. Three series of tests were conducted: 1) nonventilated fires (bedroom, small bedroom, and living room); 2) ventilated living room fires with noncombustible walls and ceiling; and 3) ventilated living room fires with combustible walls and ceiling.

Commercially available sprinkler links representative of the most sensitive on the market were employed for sprinkler activation in all the nonventilated fires and three of the ventilated fires. It was demonstrated that links considerably more sensitive than the commercial link are essential in providing adequate protection in residential fires.

In the ventilated living room fire tests with noncombustible walls and ceiling, it was demonstrated that by increasing link sensitivity, less water was required to control the fire.

In the ventilated living room fire tests with combustible walls and ceiling, the fire was fast developing and highly challenging. Adequate water application to the corner of the room, where the fire source was located, and to the walls was found to be critical in controlling such a fire. The required sprinkler operation conditions have been determined in terms of sprinkler water distribution associated with a link four or five times more sensitive than the commercial link.

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EXECUTIVE SUMMARY

Statistics on 1978 fires published by the U.S. Fire Administration show that residential fires account for 77 percent of civilian fire fatalities, 46 percent of dollar loss, and over 50 percent of fire-fighter injuries. It is evident that residential fires are our nation's number one fire problem.

For over 100 years, attempts have been made to reduce fire losses. Loss experience has provided evidence that sprinkler systems have significantly contributed to reduction of fire losses. In the 1860's, before automatic sprinkler systems appeared, annual fire losses at Factory Mutual insured properties averaged over 30 cents per $100 of insured value. Later, as sprinklers became installed in industrial and commercial properties, the figure dropped steadily to a level of 2 to 3 cents per $100 in recent years.

Since the introduction of sprinklers, fire tests have been conducted extensively to determine required sprinkler operation conditions for industrial fire protection in terms of water discharge density (water discharge rate in gpm in ratio to the designed coverage area in ft^2), sprinkler spacing, and sprinkler link temperature rating (link fusing temperature). The emphasis has always remained on industrial applications.

A National Fire Protection Association (NFPA) Standard on residential sprinkler systems (NFPA 13-D-1975) has been available since 1975. However, NFPA 13-D, resulting from relaxation of the industry-oriented sprinkler standard, produces a system too costly to be widely installed. Furthermore, the adequacy of protection provided by commercial sprinklers in accordance with the NFPA 13-D Standard has not been evaluated sufficiently in realistic residential fire tests. Thus, sprinklers, the most effective means yet devised for fire suppression, are still limited almost exclusively to the protection of industrial and commercial properties.

Due to the low ceiling height and compartmentation in residental buildings, the hot ceiling gases generated by a fire tend to descend quickly below eye level. It is vital that the sprinkler link be sufficiently sensitive to respond to the fire at a sufficiently early stage to maintain a survivable environment in the room of fire origin throughout the fire.

Standard commercial sprinklers are designed for achieving fire control with several sprinklers operating at approximately 10-ft by 10-ft spacing. The voids in the water distribution pattern of a spray usually presented behind the arms of the sprinkler frame may be filled up by adjacent sprinkler sprays. However, in residential fires, the effective control of fire by sprinklers often depends on a single sprinkler operation in the room of fire origin. It is important that sprinkler water distribution tend toward uniformity in angular distribution, so that, even if a fire starts behind the arms of the sprinkler frame, adequate amounts of water can still be delivered to the fire source. In addition, a residential sprinkler is required to protect the furniture at the periphery of the room such as a sofa, chair, and drapes, and even the combustible walls. Most standard sprinklers permitted by the current NFPA 13-D throw little water to a wall. New sprinklers with water distribution sufficient to protect the walls must be developed.

Very little effort was directed to research on residential sprinkler protection until the U.S. Fire Administration in 1976 began to sponsor several programs in the area of residential fire suppression systems. In one of these programs, Factory Mutual Research Corporation (FMRC) has been engaged in evaluating sprinkler performance in residential fire tests. In the first phase of this program, a common residential fire scenario was simulated, a cigarette dropped into the crevice of a couch in the living room, with subsequent initiation of smoldering and eventual transition to flaming fire. There were no combustibles in the test room other than the couch; windows and doors were closed. Up to the time of flaming, the major burning areas were on the cushion and the bolster of the couch and the fires had developed rather slowly. The fire was exposed and could be reached by the sprinkler spray. The required discharge rate to control such a fire is quite small.

This report covers the second phase of FMRC's program which concerns flaming-started fires. In these tests, several typical fire scenarios were selected. The second phase of the program was designed to investigate sprinkler performance as affected by sprinkler link sensitivity, link temperature rating, and water distribution in various flame-started residential fires. The information gained will serve as a guide for the sprinkler industry in developing

residential sprinklers. The research results of this program will provide a basis for new installation standards for residential sprinkler systems and will also lead to new evaluation standards for residential sprinklers for approval and listing by recognized laboratories.

Test Plan

Three test series were conducted: 1) Series 1: nonventilated fire tests; 2) Series 2: ventilated living room fire tests with noncombustible walls and ceiling; and 3) Series 3: ventilated living room fire tests with combustible walls and ceiling.

In Test Series 1, three nonventilated fire tests were conducted: a bedroom fire, a small-bedroom fire, and a living room fire. Commercial 5/16-in. orifice diameter sprinklers were used in these tests, discharging a 0.04 gpm/ft^2 application density. The sprinklers were activated by commercially available sprinkler links representative of the most sensitive on the market. The link sensitivity is expressed by its time constant defined as the time required for the link to reach an excess temperature (temperature above initial temperature of the link) which is a fraction, 0.632, of the excess gas temperature in a constant-velocity, constant-temperature gas stream. The time constant of the commercial link used was 73.9 s measured at 7.4 ft/s gas velocity.

Test Series 2 consisted of three ventilated living room fire tests with noncombustible walls and ceiling. The same commercial 5/16-in. orifice sprinklers were used in this series. In the first two tests, commercial links were used for sprinkler activation. In the third test, simulated sprinkler links with much higher sensitivity (time constant = 16.9 s at 7.4 ft/s gas velocity) were employed for sprinkler activation.

Test Series 3 included seven ventilated living room fire tests with combustible walls and ceiling. The sprinkler operation conditions investigated were link sensitivity, difference between the link temperature rating and initial link temperature, and water distribution. Four different types of sprinklers were used: 1) experimental 0.275-in. orifice sprinkler; 2) experimental 0.329-in. orifice sprinkler; 3) manufacturer's prototype 1; and 4) manufacturer's prototype 2. The commercial links were used for sprinkler activation in one of the tests with experimental 0.275-in. sprinklers. The high sensitivity simulated links were used in one test with experimental 0.275-in.

sprinklers and in two tests with experimental 0.327-in. sprinklers. Both manufacturer's prototypes were actuated by links with a 15.1-s time constant at 7.4 ft/s gas velocity.

Test Setup

The one-story building in which the tests were conducted consisted of living room with dining area, kitchen, bathroom, hall, and two bedrooms. The two bedrooms were used as instrumentation and observation rooms and the doors to the two bedrooms were closed during all fire tests. The living-dining area was 12.5 ft x 24 ft.

For the bedroom fire test, a partition with a door was erected in the middle of the living-dining area to make a 12.5-ft x 12-ft bedroom. For the small-bedroom fire test, the partition wall was moved toward the windows to make a smaller room (12.5 ft x 8.8 ft). During both tests, the windows and the door were closed.

The furnishings in the bedroom fire test consisted of a full-size bed with bedding, a headboard, a chest, a dresser, a nightstand, curtains, and wall-to-wall carpeting. The furnishings in the small bedroom fire test included a small bed with bedding, two dressers, a chair, curtains, and carpeting. In both tests, fire was started at the side of the bed by igniting a rolled sheet of newspaper on the floor.

All living room fire tests were conducted in the living room without partitions. The room was furnished with a vinyl-upholstered reclining chair near one wall, a sofa near an adjacent wall, drapes hung at the window behind the chair, a wood end table at the intersection of the two walls, a lamp on the end table, and carpeting. A match was used to ignite newspaper in a plastic wastebasket placed underneath the end table. For the tests with combustible walls and ceiling, the two walls next to the furniture were finished with plywood paneling nailed directly to the studs; the ceiling was finished with combustible tiles. In the ventilated fire tests, ventilation was provided via open windows and an entrance door.

Instrumentation

The room of fire origin was instrumented to measure: 1) gas concentrations of carbon monoxide, carbon dioxide, and oxygen at "eye level" (63 in. above the floor); 2) gas temperatures at five elevations in one location; 3) ceiling surface temperature immediately above the ignition point; and 4) gas velocities and gas temperatures near the sprinklers.

For the ventilated living room fires, additional measurements were made, such as gas temperatures at a window opening and the entry door, gas velocity at the window, etc.

Results

The adequacy of occupant protection provided by sprinklers was evaluated from measurements of carbon monoxide concentration and gas temperature at eye level in the room of fire origin. A criterion of maximum CO concentration was selected as 1500 ppm; exposure at 1500 ppm for an hour will cause death.

The criterion adopted for evaluating the heat hazard during the program was that the gas temperature at eye level should be less than 200°F. Gas temperature of more than 200°F in a fire environment causes loss of consciousness and death within several minutes.

Measurements of ceiling surface temperature above the fire source were used to assess the ability of residential sprinklers to provide property protection. For adequate property protection, a limit of 500°F ceiling surface temperature was selected; cellulosic and plastic material usually begin to decompose vigorously at about this temperature.

In all the nonventilated fire tests, commercially available sprinkler links were employed for sprinkler activation. In the small bedroom fire, due to the small room size, hot ceiling gases descended quickly to eye level. At the time of sprinkler activation, the eye-level gas temperature near the center of the room had already reached 241°F, exceeding the adopted critical value for eye-level gas temperature. In order to maintain a survivable environment in the room of fire origin throughout this fire, a sprinkler should respond at an earlier stage of the fire; in other words, the sprinkler link must be more sensitive than the commercial link. In the other nonventilated fires, bedroom and living room, the environment was deemed survivable at the time of sprinkler activation because of the large room size.

The fire in the bedroom was not shielded from sprinkler spray. A local water application of 0.02 gpm/ft^2 on the fire source was demonstrated to be adequate in suppressing the fire.

In the living room fire tests, combustibles were located in the northeast corner of the room; fire was started on the left side of a reclining chair, then spread to the curtains behind the chair. Fire on the left side and backside of the chair was shielded from direct sprinkler water impingement. In order to suppress such a challenging fire and cool the fire gases, considerably more water was required over the fire source than in the bedroom fire. An average water application density, w_c, over a 5-ft x 5-ft floor area in the corner of a 15-ft x 15-ft coverage area without walls was used to indicate the amount of sprinkler water delivered to the corner of the living room. The vertical application density, w_v, over a 1-ft wide x 2.5-ft high area on the wall above the chair indicates the amount of water delivered to protect the wall from igniting by the source fire.

In the nonventilated living room fire with combustible walls and ceiling, the sprinkler delivering an average application density, w_c, of 0.015 gpm/ft^2 was not capable of suppressing the fire and cooling the gases sufficiently. Judging from the ceiling gas temperature and velocity measurements in the living room, it is expected that the sprinklers in the hallway and kitchen would have been actuated. Although the application density, w_c, was not sufficient, the combustible ceiling tile and panel above the window did not ignite, due to lower heat release rate in the nonventilated fire. With regard to the vertical application density, w_v, the value of 0.011 gpm/ft^2 delivered by the sprinkler was sufficient to prevent fire spread to the wall.

In the ventilated living room fire tests, at the time of sprinkler activation with the commercial link the fire was already in its very fast accelerating stage, the entire furnished corner of the room was engulfed in flames, and flames swept across the ceiling. In order to have a somewhat safer environment at the time of sprinkler activation, it was deemed necessary to employ a more sensitive link than the commercial link, as in the nonventilated small bedroom fire.

In the ventilated living room fire tests with noncombustible walls and ceiling, it was demonstrated that, by reducing the sprinkler link response

time, less water was required to control the fire. A sprinkler activated by the simulated high-sensitivity link rated at 140°F, delivering an average application density, w_c, of 0.015 gpm/ft^2, was capable of providing adequate life-safety and property protection in the room of fire origin. However, a value of w_c of 0.015 gpm/ft^2 was not sufficient to suppress the fire and cool the fire gases to prevent excessive sprinkler openings in the hallway and the kitchen outside the living room.

When combustible walls and ceiling were present in the living room, it was even more critical to use a high-sensitivity link to activate the sprinkler at a time when the major burning activity was still limited to the chair. Using the high-sensitivity simulated link, tests with experimental sprinklers have made it possible to bracket the corresponding application density, w_c, and vertical application density, w_v, required to control the high-challenge fire.

Manufacturer's prototype sprinklers with a link of 15.1-sec time constant rated at 136°F were subsequently investigated in the same ventilated living room fire. The critical value of the application density, w_c, was found to be 0.035 gpm/ft^2 in order to suppress the fire source in the corner and prevent plywood panels and combustible ceiling from igniting. In addition, vertical application density, w_v of 0.012 gpm/ft^2 on the wall was demonstrated to be adequate to prevent fire jump from the backside of the chair to the wall.

In the tests in which manufacturer's prototype 2 was demonstrated to be successful in controlling the challenging ventilated fire, only one sprinkler was activated and the sprinkler discharge rate was 15 gpm covering a 12-ft x 12-ft area. The prototype discharges a rather uniform pattern in the angular distribution so that, even if a fire starts behind the arms of the sprinkler frame, an adequate amount of water can be expected to be delivered to the fire source.

In conclusion, significantly more sensitive links than the commercially available link, representative of the most sensitive on the market, are essential to provide adequate life-safety and property protection in residential fires. The required sprinkler operation conditions for control of a typical high-challenge, fast-developing residential fire have been determined in terms of water distribution associated with a link four or five times as sensitive as the commercial link.

The results obtained in the program will 1) serve as a guide for the development of residential sprinklers, 2) establish a foundation for new installation standards for residential sprinkler systems, and 3) lead to new standards for approval and listing of residential sprinklers by recognized laboratories.

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I
INTRODUCTION

The statistics on 1978 fires published by the U. S. Fire Administration[1] show that residential fires account for 77 percent of civilian fire fatalities, 46 percent of dollar loss and over 50 percent of fire-fighter injuries. It is quite evident that residential fires are our nation's number one fire problem.

For over 100 years, attempts have been made to reduce fire losses, through improved and more extensive fire service operation, public education, codes and regulations, and suppression systems. Loss experience has provided evidence that sprinkler systems in particular have significantly contributed to a reduction of fire losses. In the 1860's before automatic sprinkler systems appeared, annual fire losses at Factory Mutual insured properties averaged over 30 cents per $100 of insured value. Later, as sprinklers became installed in industrial and commercial properties, the figure dropped steadily to a level of 2 to 3 cents per $100 in recent years[2].

After 1850, perforated pipe systems were adopted by the New England Textile Manufacturers for fire protection. In the late 1870's, these manually actuated systems were followed by the more effective Parmelee automatic sprinkler which consisted of a salt shaker or turbine type distributor covered with a cap held to the distributor with a low-temperature solder. When exposed to fire, the solder would melt, the cap would fall off and water would be distributed to the fire below. In the 1880's, Grinnell (currently, the Grinnell Fire Protection Systems Company) joined Parmelee and introduced an improved sprinkler which essentially resembles today's sprinkler. In the early 1950's, as a result of Factory Mutual's research, a sprinkler with significantly improved distribution was developed and adopted as the present standard sprinkler.

Since the introduction of sprinklers, fire tests have been conducted extensively to determine sprinkler operation conditions for industrial fire protection in terms of water discharge density (water discharge rate in gpm in ratio to the designed coverage area in ft^2), sprinkler spacing, and sprinkler link temperature rating (link fusing temperature). In recent years, due to the widespread use of plastic materials, standard sprinklers have encountered difficulties in meeting some of the challenges involved with plastic storage. Factory Mutual

has directed considerable effort toward the research and development of improved industrial sprinkler protection; the emphasis has always remained on industrial applications.

A National Fire Protection Association (NFPA) Standard on residential sprinkler systems (NFPA 13-D-1975)[3] has been available since 1975. However, NFPA 13-D, resulting from relaxation of the industry-oriented sprinkler standard, produces a system too costly to be widely installed. Furthermore, the adequacy of protection provided by commercial sprinklers in accordance with NFPA 13-D has not been evaluated sufficiently in realistic residential fire tests. Sprinklers, the most effective means yet devised for fire suppression, are still limited almost exclusively to the protection of industrial and commercial properties. There was very little effort directed to research on residential sprinkler protection[4] until the U.S. Fire Administration began to sponsor several programs in the area of residential fire suppression systems in 1976. In one of these programs FMRC has been engaged in evaluating sprinkler performance in residential fire tests.

Since the cause of the majority of fatal residential fires has been attributed to "smoking" in a living room or bedroom,[5] all the tests conducted in the first phase of the program at FMRC for evaluation of sprinkler discharge conditions were smoldering-started living room fires[6]. The fire scenario simulated in the experimental program was a cigarette dropped into the crevice of a couch in the living room, with subsequent initiation of smoldering and eventual transition to flaming fire. There were no combustibles in the test room other than the couch; windows and doors were closed. For the kind of couches used in the tests, transition to flaming occurred after a smoldering interval of approximately one hour. At the time of flaming, the major burning areas were on the cushion and the bolster of the couch, and the fires developed rather slowly. Employing a commercially available, relatively fast-responding sprinkler link, the environment was still deemed survivable at the time of sprinkler activation. Since the fire was exposed and could be reached by the sprinkler spray, the required discharge rate to control the fires was quite small, only 6 gpm for a 12-ft by 12-ft coverage area.

This report covers the second phase of FMRC's program, which concerned flaming-started fires. In these tests, five fire scenarios were selected: 1) bedroom

fire without ventilation; 2) small-bedroom fire without ventilation; 3) living room fire without ventilation; 4) living room fire with ventilation, with noncombustible walls and ceiling; and 5) living room fire with ventilation, with combustible walls and ceiling.

Due to the low ceiling height and small compartments in residential buildings, the hot gases generated by a fire tend to descend quickly below eye level. It is vital that the sprinkler link be sufficiently sensitive to respond to the fire at a sufficiently early stage to maintain a survivable environment in the room of fire origin throughout the fire.

Furthermore, standard commercial sprinklers are designed for achieving fire control with several sprinklers operating at approximately 10-ft by 10-ft spacing. The water spray (umbrella) of two adjacent commercial sprinklers will overlap 3 ft below the sprinkler level. The voids in the water distribution pattern of a spray behind the arm of the sprinkler frame may be filled up by adjacent sprinkler sprays. However, in residential fires, the effective control of fire by sprinklers often depends on a single sprinkler operation in the room of fire origin. It is essential that sprinkler water distribution tend toward uniformity in angular distribution, so that, even if a fire starts behind the arms of the sprinkler frame, adequate amounts of water can still be delivered to the fire source. In addition, combustible items such as sofa, chair, bureau, and drapes are often placed close to or against the walls. A residential sprinkler is required to protect the furniture at the periphery of the room and the walls. The current NFPA 13-D Standard permits the use of standard sprinklers in residences to cover a 16-ft by 16-ft floor area at approximately 25 gpm water discharge rate. Most of the standard sprinklers throw little water to the upper portion of a wall which is more than 6 ft from the sprinkler. New sprinklers with water distribution to protect the walls must be developed and the sprinkler spacing in the current NFPA 13-D Standard can then be modified accordingly.

Through the present series of fire tests, the effects of sprinkler link sensitivity, link temperature rating, and water distribution on sprinkler performance have been investigated. The required sprinkler operation conditions in terms of these parameters have been determined for controlling fast-developing, high-challenge residential fires.

The information gained in this program will provide a basis for the revision of the current NFPA 13-D Standard and other installation standards of residential sprinkler systems, and will also serve as a guide for the development of residential prototype sprinklers. In addition, the research results of this program will also lead to new standards of residential sprinklers for approval and listing by recognized laboratories.

II

DESIGN OF TEST PROGRAM

The fire tests were designed to investigate sprinkler performance as affected by sprinkler response time, water discharge rate, and water distribution in various typical flame-started residential fires.

The response time of a sprinkler in a fire depends on 1) the gas velocity and gas temperature histories (fire development) adjacent to the sprinkler, and 2) the sprinkler link sensitivity and its temperature rating. The link sensitivity is expressed by its time constant, defined as the time required for the link to reach an excess temperature (temperature above initial temperature of the link) which is a fraction, 0.632, of the excess gas temperature in a constant-velocity, constant-temperature gas stream. The time constant depends predictably upon gas velocity and is independent of gas temperature[7]. The time constants of the sprinkler links and the simulated sprinkler links used in this program were measured in a hot air wind tunnel[7] at 7.4 ft/s air velocity and 367°F temperature. All the time constants cited hereafter are referenced to a velocity of 7.4 ft/sec.

Three test series were conducted: 1) Series 1: non-ventilated fire tests; 2) Series 2: ventilated living room fire tests with noncombustible walls and ceiling; and 3) Series 3: ventilated living room fire tests with combustible walls and ceiling.

2.1 TEST SERIES 1: NONVENTILATED FIRE TESTS

Three nonventilated fire tests were conducted: a bedroom fire, a small-bedroom fire, and a living room fire (Table I). Commercial 5/16-in. orifice diameter sprinklers were used in these tests. The sprinklers were activated by relatively fast-responding commercially available sprinkler links with a time constant of 73.9 sec.

2.2 TEST SERIES 2: VENTILATED LIVING ROOM FIRE TESTS WITH NONCOMBUSTIBLE WALLS AND CEILING

This test series consisted of three ventilated living room fire tests with noncombustible walls and ceiling. The same commercial 5/16-in. orifice sprinklers were used in this series. In one of the tests, simulated sprinkler links

TABLE I

SPRINKLER VARIABLES OF TEST SERIES 1, NONVENTILATED FIRE TESTS

Test No.	Sprinkler	Sprinkler Orifice Dia. (in.)	K* factor, $(gpm/psi^{\frac{1}{2}})$	Link Sensitivity at 7.44 ft/s gas velocity (sec)	Link Temp. Rating (°F)	Initial Link Temp. (°F)	Water Discharge Rate (one sprinkler operation) (gpm)	Water Discharge Rate (two sprinkler operations) (gpm)
S1.1 bedroom fire	Commercial 5/16-in. Orifice Sprinkler	0.309	2.01	73.9	165	86	6	Not Applicable
S1.2 small-bedroom fire	Commercial 5/16-in. Orifice Sprinkler	0.309	2.01	73.9	165	77	4.3	Not Applicable
S1.3 living-room fire	Commercial 5/16-in. Orifice Sprinkler	0.309	2.01	73.9	165	94	6	6+6

*K factor, a number indicating the sprinkler discharge capacity, is defined as the discharge rate, W, divided by the square root of the discharge pressure, Δp, i.e., $K = W\ (gpm)/(\Delta p\ (psig))^{\frac{1}{2}}$

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with higher sensitivity (time constant: 16.9 sec) were employed for sprinkler activations. Table II lists sprinkler variables for the three tests.

2.3 TEST SERIES 3: VENTILATED LIVING ROOM FIRE TESTS WITH COMBUSTIBLE WALLS AND CEILING

Test Series 3 includes seven ventilated living room fire tests with combustible walls and ceiling. The sprinkler variables are summarized in Table III. The sprinkler operation conditions investigated were link sensitivity, temperature difference between the link temperature rating and initial link temperature, and water distribution.

TABLE II

SPRINKLER VARIABLES OF TEST SERIES 2,
VENTILATED LIVING ROOM FIRE TESTS WITH NONCOMBUSTIBLE WALLS AND CEILING

Test No.	Sprinkler	Sprinkler Orifice Dia. (in.)	K* factor, (gpm/psi$^{\frac{1}{2}}$)	Link Sensitivity at 7.44 ft/s gas velocity (sec)	Link Temp. Rating (°F)	Initial Link Temp. (°F)	Water Discharge Rate (one sprinkler operation) (gpm)	Water Discharge Rate (two sprinkler operations) (gpm)
S2.1	Commercial 5/16-in. Orifice Sprinkler	0.309	2.01	73.9	165	69	6	6+6
S2.2	Commercial 5/16-in. Orifice Sprinkler	0.309	2.12	73.9	165	76	9	9+9
S2.3	Commercial 5/16-in. Orifice Sprinkler	0.309	2.01	16.9	140	69	6	6+6

*K factor, a number indicating the sprinkler discharge capacity, is defined as the discharge rate, W, divided by the square root of the discharge pressure, Δp, i.e., $K = W\ (gpm)/(\Delta p\ (psig))^{\frac{1}{2}}$

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TABLE III

SPRINKLER VARIABLES OF TEST SERIES 3,
VENTILATED LIVING ROOM FIRE TESTS WITH COMBUSTIBLE WALLS AND CEILING

Test No.	Sprinkler	Sprinkler Orifice Dia. (in.)	K* factor, (gpm/psi$^{\frac{1}{2}}$)	Link Sensitivity at 7.44 ft/s gas velocity (sec)	Link Temp. Rating (°F)	Initial Link Temp. (°F)	Water Discharge Rate (one sprinkler operation) (gpm)	Water Discharge Rate (two sprinkler operations) (gpm)
S3.1	Exp 0.274	0.274	2.12	73.9	165	70	9	9+9
S3.2	Exp 0.274	0.274	2.12	16.9	143	63	9	9+9
S3.3	Exp 0.329	0.329	3.11	16.9	143	67	12	9+9
S3.4	Exp 0.329	0.329	3.11	16.9	163	69	12	9+9
S3.5	Manufacturer's Prototype 1	.311	2.69	15.1	136	66	12	9+9
S3.6	Manufacturer's Prototype 2	L .433** W .223	3.00	15.1	136	71	15	
S3.7	Manufacturer's Prototype 2	L .433** W .233	3.00	15.1	136	76	15	

* K factor, a number indicating the sprinkler discharge capacity, is defined as the discharge rate, w, divided by the square root of the discharge pressure, Δp, i.e., $K = w(gpm)/(\Delta p(psig))^{\frac{1}{2}}$

**milled oval waterway L: length, W: width

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III
TEST SETUP

3.1 TEST FACILITY

The fire tests were conducted in one of FMRC's test buildings in Norwood, Massachusetts. Figure 1 is a plan view of the test structure relative to an attached fire test building. The test structure is a type AL Parkersburg Building[5,8], constructed of galvanized steel and measuring 24 ft wide x 44 ft long x 14 ft eave height. The building contains a 741 ft^2 apartment area, a 139 ft^2 instrument room and a 24-ft long leg of a simulated corridor. The other leg of the simulated corridor extends into the attached test building and is 34 ft long.

The ceiling height in the apartment area, instrument room, and corridor is uniformly 8 ft. With the exception of the north half of the living room, the ceiling was constructed with 2-ft x 4-ft Armstrong "Fire Guard" ceiling panels suspended from the beams of the building structure. Figure 2 shows the layout of the test apartment. Wall partitions are 5/8-in. gypsum boards framed in "Unistrut" channels (Unistrut Corporation). An overhead working space, floored with steel grating resting on steel channeling, affords access to ceiling instrumentation. All the living room fire tests were conducted in the living room area of the test apartment. During all tests, the doors to the instrumentation room (close fitting), the observation room (11/16-in. undercut), and the bathroom were closed. For the nonventilated living room fire test, the windows in the living room and the entry door (11/16-in. undercut) to the apartment were closed. During the ventilated living room fire tests, two windows in the north wall and the entry door were fully open. For the bedroom fire test, a wall partition was erected 12 ft from the north wall in the living room to convert the northern area of the living room into a simulated bedroom. For the small bedroom fire test, the partition was moved to within 8.8 ft of the north wall. During both tests, the windows at the north wall and the door in the partition wall were closed.

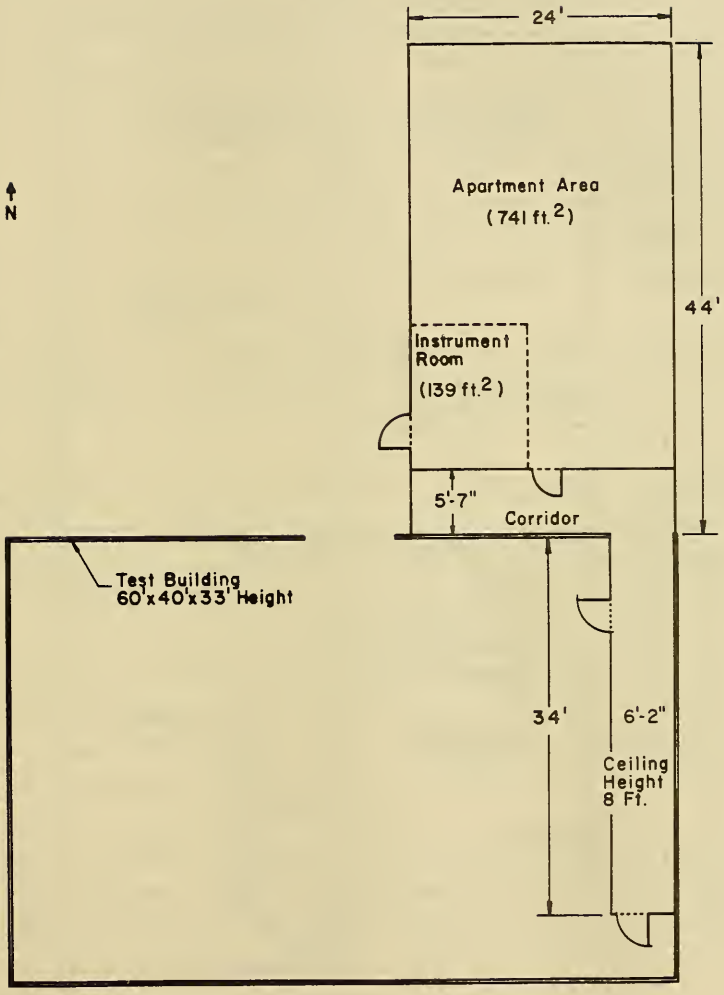


FIGURE 1 TEST STRUCTURE RELATIVE TO EXISTING TEST BUILDING

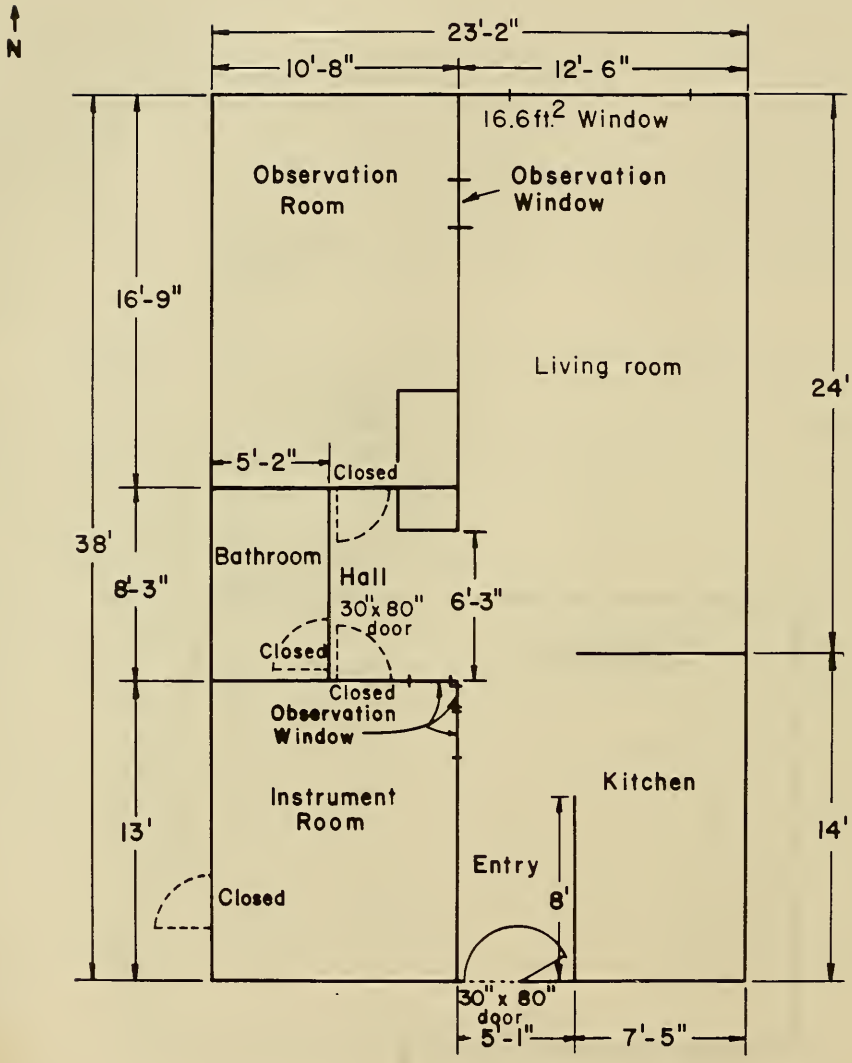


FIGURE 2 TEST APARTMENT FLOOR PLAN

3.2 FURNISHINGS

3.2.1 Test Series 1

Scale layouts of the furnishings with location coordinates for the bedroom fire, small-bedroom fire, and living room fire tests are shown in Figures 3, 4, and 5 respectively. Full descriptions of the bedroom, small bedroom, and living room furnishings are included in Tables IV, V and VI.

A suspended ceiling was made of 2-ft x 4-ft combustible ceiling panels (297C Grenoble Temlock, Armstrong Cork Corporation), 1/2-in. thick, consisting of loblolly pine, oak and cornstarch. Plywood panels (3/16-in. thick)were nailed to spruce studs (1 1/2 in. x 3 5/16 in.) mounted directly to the existing north and east walls. For the living room fire tests, the plywood paneling on the east wall only extended to within 12 ft from the northeast corner. For the two bedroom fire tests, the partition was constructed with plywood panels nailed directly over spruce studs (1 1/2 in. x 3 5/16 in.).

Photographic views of the pretest appearances of the bedroom, small bedroom, and living room are shown in Figures 6(a), (b), and (c) respectively.

3.2.2 Test Series 2

Armstrong "Fire Guard" ceiling panels (2 ft x 4 ft x 1/3 in. thick, Model 915, Armstrong Cork Corporation) were fastened to the 5/8-in. gypsum board ceiling in the northern half of the living room. Instead of plywood panels, 5/8-in. thick gypsum boards were nailed to the wood studs on the north and east walls.

For all three tests, identical sets of furnishings were used. These furnishings were the same as those used in the living room fire test of Series 1 (Table VI) with the exception that the hassock was omitted and the end table was constructed with compressed wood slab (26 in. x 19 1/2 in. x 1/2 in. thick) and wood studs (1 1/2 in. x 1 1/2 in. x 19 in. high).

In all tests, the window curtains were pulled aside as shown in Figure 7. The dimensions and positions of the window openings, are also shown in Figure 7. The relative positions of the rest of the furnishings with respect to the east and north walls (Figure 7) remained the same as those of the living room fire test of Series 1.

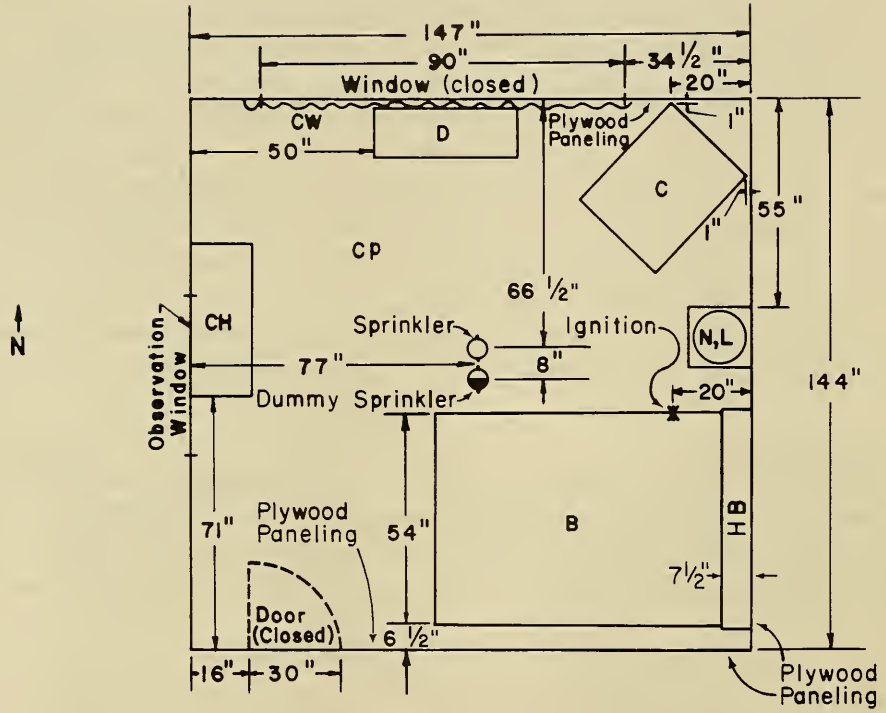


FIGURE 3 FURNISHINGS IN THE BEDROOM

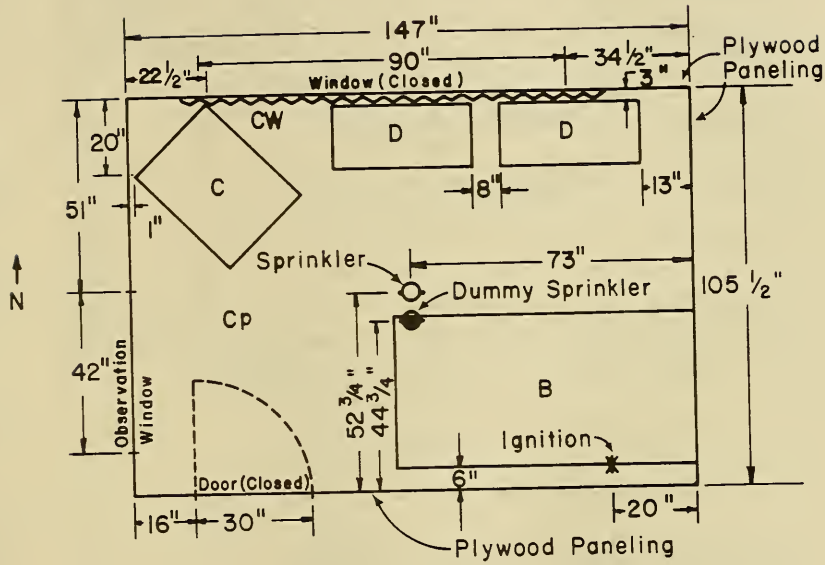


FIGURE 4 FURNISHINGS IN SMALL BEDROOM

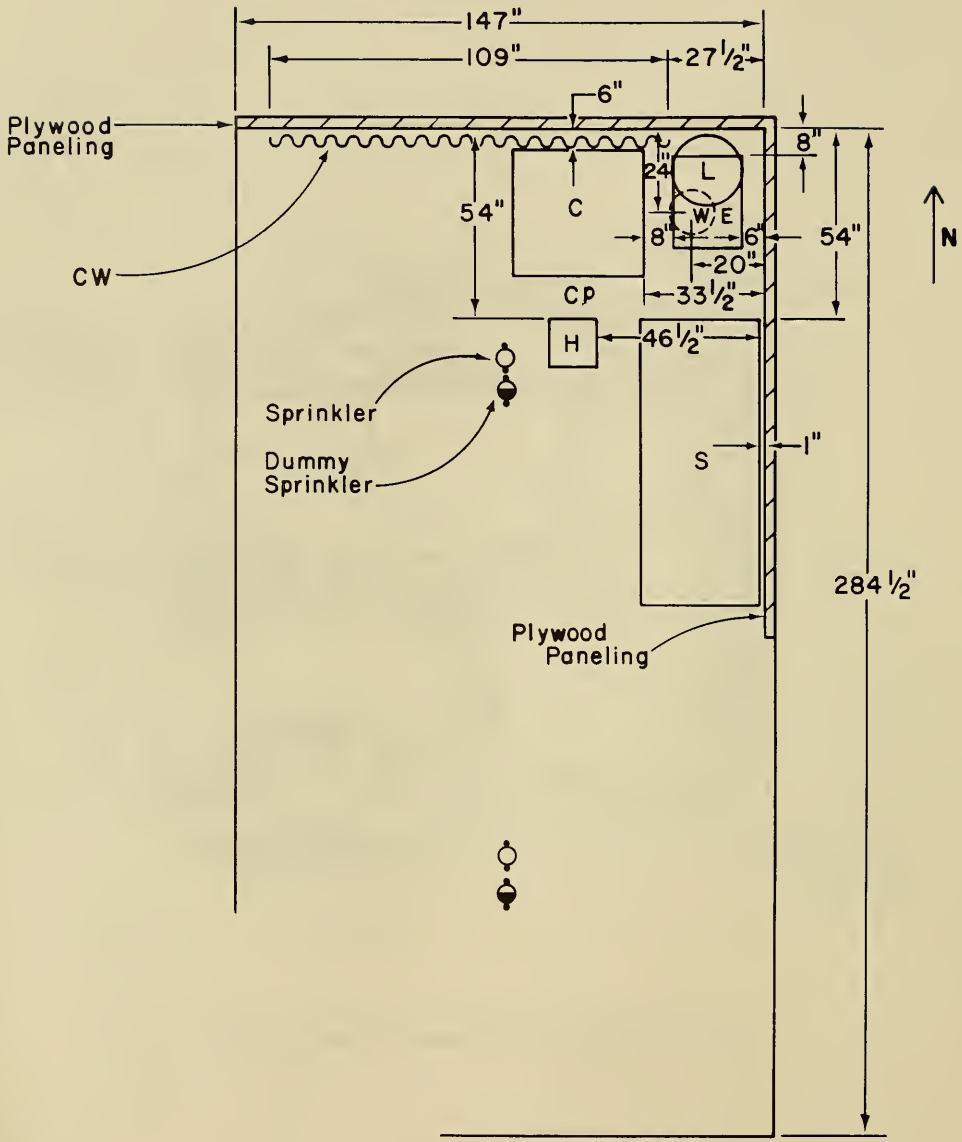


FIGURE 5 FURNISHINGS IN NON-VENTILATED LIVING ROOM

TABLE IV

FURNISHINGS IN BEDROOM

Item	Code (Fig. 3)	No. of Units	Dimensions (in.) and Description
Bed (full size)	B		
Mattress		1	54Wx75Lx4H, polyurethane, polyester & rayon cover Sears* 1K7952N2
Box Spring		1	54Wx75Lx4H, wood frame, steel springs, cotton padding, cheese cloth bottom cover. Sears 1K7952N2
Frame		1	Steel, Sears 1K74011L
Headboard	HB	1	54Wx7 1/2Lx35H, hardboard (with book shelf) Sears 1K75764NH
Bottom Sheet	B	1	Fitted full size, 50% cotton, 50% polyester Sears 96K6941
Top Sheet	B	1	Flat full size, 50% cotton, 50% polyester, Sears 96K6948
Blanket	B	1	Full size, 100% acrylic, Sears 96K8751A-543
Bedspread	B	1	Full size, 100% cotton, Sears 24K14011H-561
Pillows	B	2	20Wx26L, polyester fill, cotton cover Sears 96K5305
Pillow Cases	B	2	20Wx30L, 50% cotton, 50% polyester, Sears 96K6945
Curtains (2 panels/set)	CW	2 (Sets)	72Wx63L, 100% cotton, Sears 24K14029H
Nightstand (one drawer)	N	1	15Wx16Lx25 1/2H, solid knotty pine with hard-board back, one coat of polyurethane finish Sears 1K11011L
Dresser (six drawers)	D	1	37Wx13 1/2Lx29H, solid knotty pine with hard-board back, one coat of polyurethane finish Sears 1K10866N
Chest	CH	1	36Wx17Lx46H, pine finish, pine stock, fiber-board plastic laminated top, Sears 1K13905N
Lamp	L	1	32H, shade 13 dia 15H, glass base cloth shade, local dept. store
Chair	C	1	28Wx35Lx33H, pine frame, steel springs, 2 piece polyurethane vinyl coated cushions
Carpet	CP	1	144 x 146, indoor/outdoor olefin pile, latex backed, Sears 37K5031-NPH-6

*Sears Catalog Spring/Summer 1978 (K)

TABLE V

FURNISHINGS IN SMALL BEDROOM

Item	Code (Fig. 4)	No. of Units	Dimensions (in.) and Description
Bed	B	1	39Wx79L, mate's bed, solid hardwood, 2 guided drawers, maple finish, with mattressboard: 1 3/4-in. thick wood, covered in polypropylene nonwoven fabric, Sears 1K6761N2
Mattress	B	1	39Wx79Lx4H, polyurethane foam covered with non-woven polyester fabric, Sears 1K70112N
Bottom Sheet	B	1	Twin fitted, 50% cotton, 50% polyester Sears 96K6940
Top Sheet	B	1	Twin flat, 50% cotton, 50% polyester Sears 96K6944
Blanket	B	1	Twin size, 100% acrylic, Sears 96K8750H-543
Bedspread	B	1	Twin size, 100% cotton, Sears 24K14012H-561
Pillow	B	1	20Wx26L polyester fill cotton cover Sears 96K5305
Pillow Case	B	1	20Wx30L, 50% polyester, 50% cotton, Sears 96K6945
Curtains (2 panels/set)	CW	2 (sets)	72Wx63L, 100% cotton, Sears 24K14029H
Dresser (6 drawer)	D	2	36Wx13 1/2Lx29H, Solid knotty pine, with hard-board back, one coat of polyurethane finish, Sears 1K10866N
Chair	C	1	28Wx35Lx33H Pine frame, steel springs, 2-piece polyurethane vinyl coated cushions
Carpet	CP	1	147Wx105L, Indoor/outdoor olefin pile, latex backed, Sears 37K5031-NPH-6

TABLE VI

FURNISHINGS IN LIVING ROOM

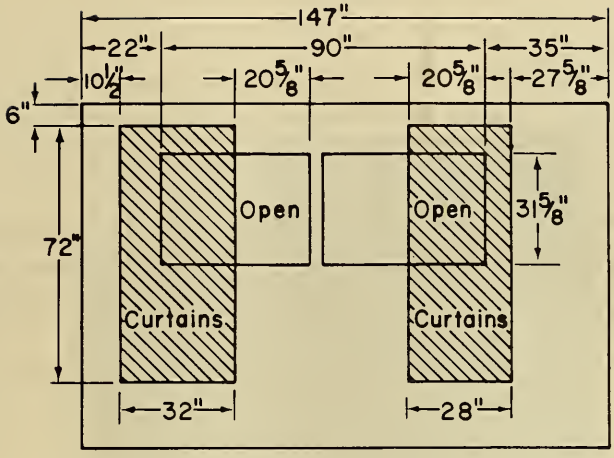
Item	Code (Fig. 5)	No. of Units	Dimensions (in.) and Description
Sofa	S	1	83Wx36Lx25H, Body-80% cotton felt, 20% urethane foam, cushions-80% urethane foam, 20% polyester fiber cover-herculon, J. Homestock #201310048
Hassock	H	1	14Wx14Lx12H, fill-polyurethane foam, Excelsior base, Sears 24K86596LH
Chair	C	1	36Wx36Lx39H, Blended cotton felt, 40% (cotton liners 70%, cotton pickers 30%), polyurethane foam 50%, cellulose fiber pad 10%, cover-vinyl, J. Homestock #243-1-432-0
End table	E	1	26Wx19 1/2Lx19 1/2H, Pine, stain and varnish, J. Homestock #31310-2016
Curtains	CW	12	6 panels (40Wx72L) 56% cotton 27% rayon, 9% acetate, 8% polyester, 6 sheer panels (40Wx72L, 1.5 oz/yd) Batiste fabric woven/100% polyester Sears 24K4507H
Carpet	CP	1	96Wx96L, Indoor/outdoor olefin pile, latex backed, Sears 37K5031-NPH-6
Lamp	L	1	15 dia x 15 H, lamp shade made by Patterson Shade Co, Style No. 2540
Wastebasket	W	1	Model 2132, Cities Service Co., Box 826 Pittsburgh, Pa. 15230

a) Bedroom,Test S1.1

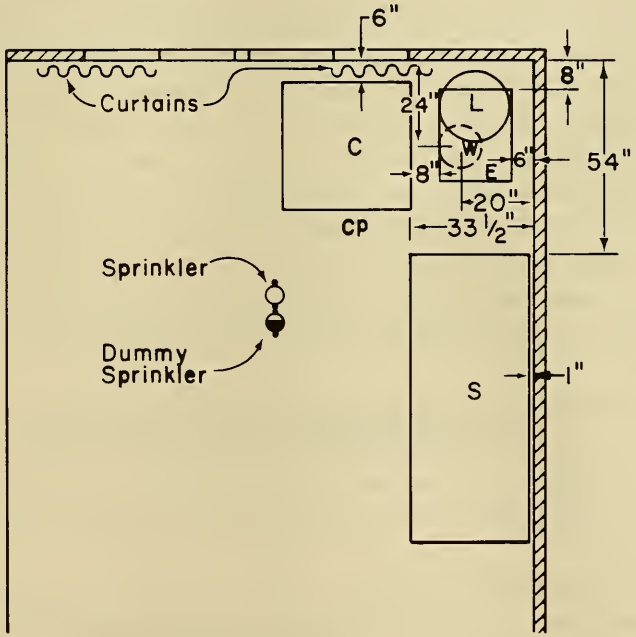
b) Small bedroom,Test S1.2

c) Living Room ,Test S1.3

FIGURE 6 PRE-TEST APPEARANCE OF TESTS S1.1, S1.2, S1.3



NORTH WALL



FLOOR PLAN

FIGURE 7 FURNISHINGS IN THE VENTILATED LIVING ROOM

3.2.3 Test Series 3

Throughout the test series, sets of furnishings identical to those for Test Series 2 were used. The curtains were hung in the same manner shown in Figure 7. The layout of other furnishings remained the same as that of the living room fire test of Series 1.

Combustible ceiling panels (2 ft x 4 ft x 1/2 in. thick, 297C Grenoble Temlock, Armstrong Cork Corporation) were fastened to 5/8-in. gypsum board ceiling in the northern half of the living room. Plywood panels (3/16-in. thick) were nailed to the studs on the north and east walls.

A photographic view of the ventilated living room with furnishings is shown in Figure 8.

3.3 INSTRUMENTATION

3.3.1 Test Series 1

For the nonventilated fire tests, the room was instrumented to measure: 1) gas concentrations of carbon monoxide, carbon dioxide, and oxygen at "eye level" (63 in. above the floor); 2) gas temperatures at five elevations (93, 84, 63, 36, and 6 in. above the floor) in one location; 3) ceiling surface temperature immediately above the ignition point; 4) optical density (a measure of smoke obscuration) at "eye level" (63 in. above the floor); and 5) gas velocities and gas temperatures near the sprinklers (3 in. below ceiling level). Figures 9, 10, and 11 show the instrumentation plans for the bedroom, small bedroom and living room fire tests. All data signals, except optical density, were monitored by a data acquisition system with a Hewlett-Packard 2100 S computer. Every second, the system scanned the data channels and logged the data on a computer disk.

Carbon monoxide, carbon dioxide and oxygen were measured at a single location near the center of the room using Beckman CO, CO_2, and O_2 analyzers. The gas sample was drawn to the analyzers through 3/8-in. ID (1/2-in. OD) aluminum tubes and Tygon tubing and then cleaned through a glass wool filter, a condenser, and a desiccant.

The delay times for the CO, CO_2, and O_2 measurements were 16.6, 15.4, and 24.5 sec respectively. All data presented in the report have been adjusted for delays of the sampling system.

Living Room ,Test S3.3

FIGURE 8 PRE-TEST APPEARANCE OF TEST S3.3

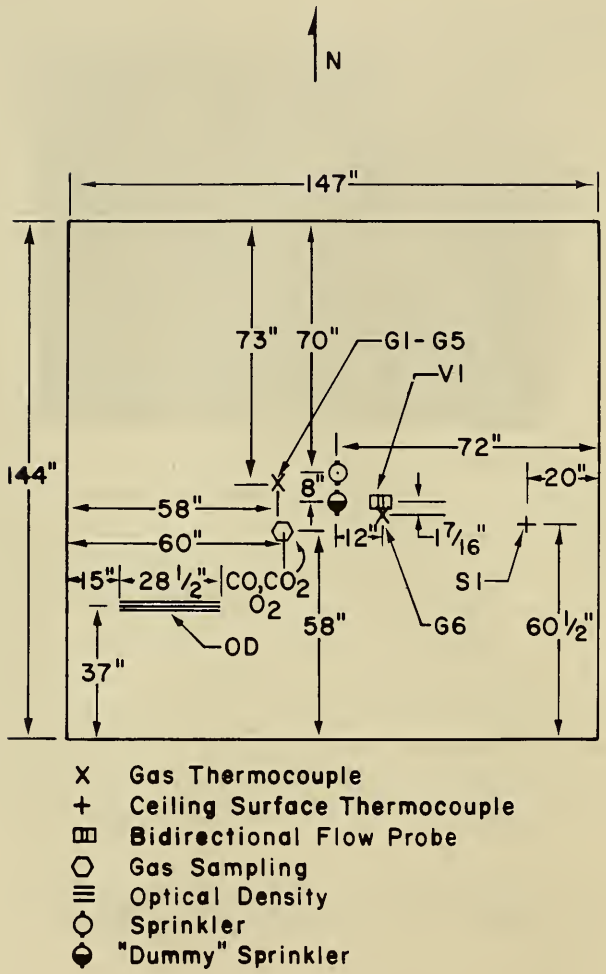


FIGURE 9 BEDROOM INSTRUMENTATION LOCATIONS

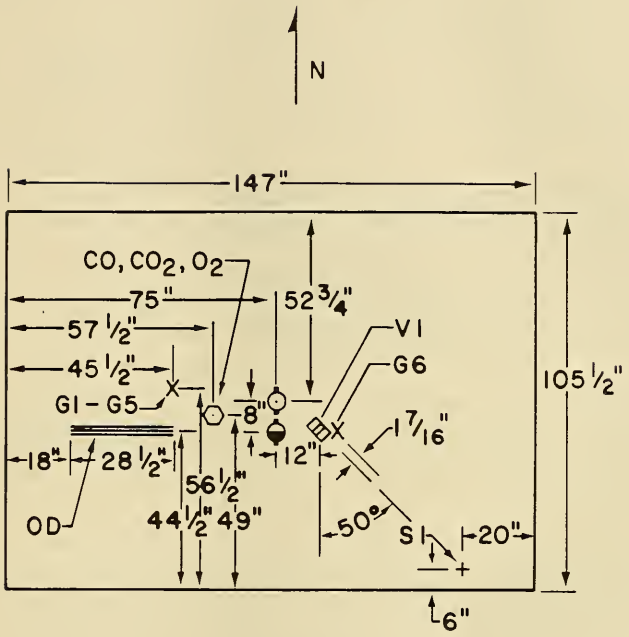


FIGURE 10 SMALL BEDROOM INSTRUMENTATION LOCATIONS

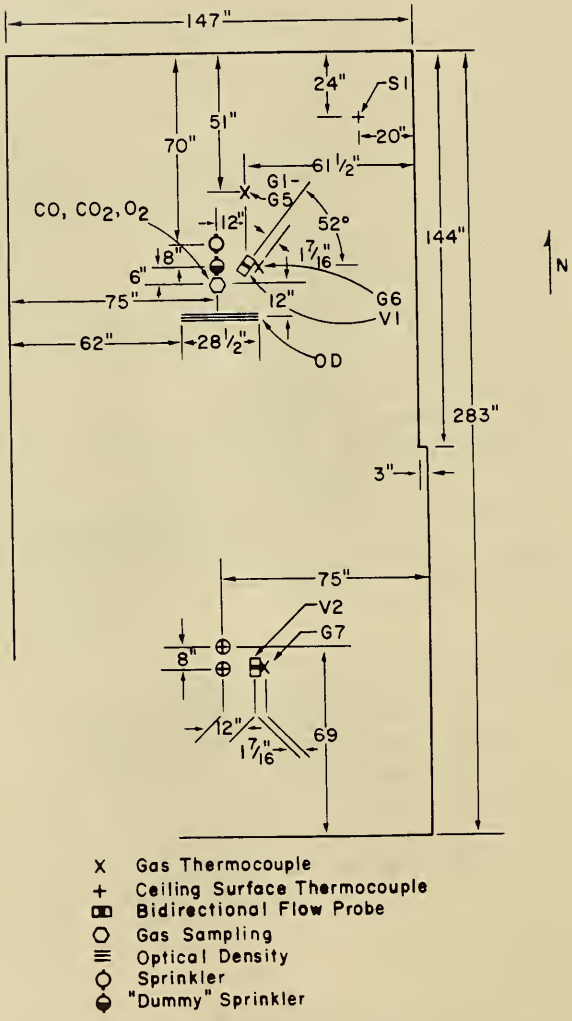


FIGURE 11 LIVING ROOM INSTRUMENTATION LOCATIONS

Gas velocities in the vicinity of the sprinklers were measured 3 in. below the ceiling using bidirectional flow probes[9], which sense and indicate flows in opposite directions with equal sensitivity and are relatively insensitive to flow deviation from probe axial direction. The probes were connected to individual electronic manometers (Datametric Barocel). With this system, it was possible to measure reliably velocities down to 1 ft/sec. The locations and orientations of the flow probe in the bedroom, small bedroom, and living room are shown in Figures 9, 10, and 11 respectively.

Thermocouples, fabricated from 30-gage, chromel-alumel thermocouple wire (inconel sheath), were used to measure gas temperatures. A vertical traverse of five thermocouples (93, 84, 64, 36, and 6 in. from the floor) was installed in the room of fire origin (G1 to G5 in Figures 9, 10, and 11). A 1/2-in. wide "Unistrut" channel was used to support the five thermocouples and shield them from direct water impingement (Figure 12).

Adjacent to the velocity probe, a gas thermocouple (G6 in Figures 9 and 10; G6 and G7 in Figure 11) was placed 1 7/16 in. from the probe axis and shielded from the sprinkler by the probe to measure gas temperature in the vicinity of the sprinkler.

The ceiling surface temperature immediately above the ignition source (Figures 9, 10, and 11) was measured by a thermocouple fabricated from 28-gage chromel-alumel thermocouple wire. The thermocouple was imbedded in a shallow groove filled with Kaowool paste such that the thermocouple bead was flush with the ceiling surface.

3.3.2 Test Series 2

For the ventilated, noncombustible living room fire tests the amount of instrumentation was increased from that of the previous test series. The following additional measurements were made:

1) gas velocity at the opening of the northwest window (see Figure 13) 5 13/16 in. or 25 13/16 in. from the top edge of the window. (For Test S2.1 velocities at the first and second sprinkler and the higher window location were measured; for Tests S2.2 and S2.3 velocities at the first sprinkler and at the lower window location were measured.);

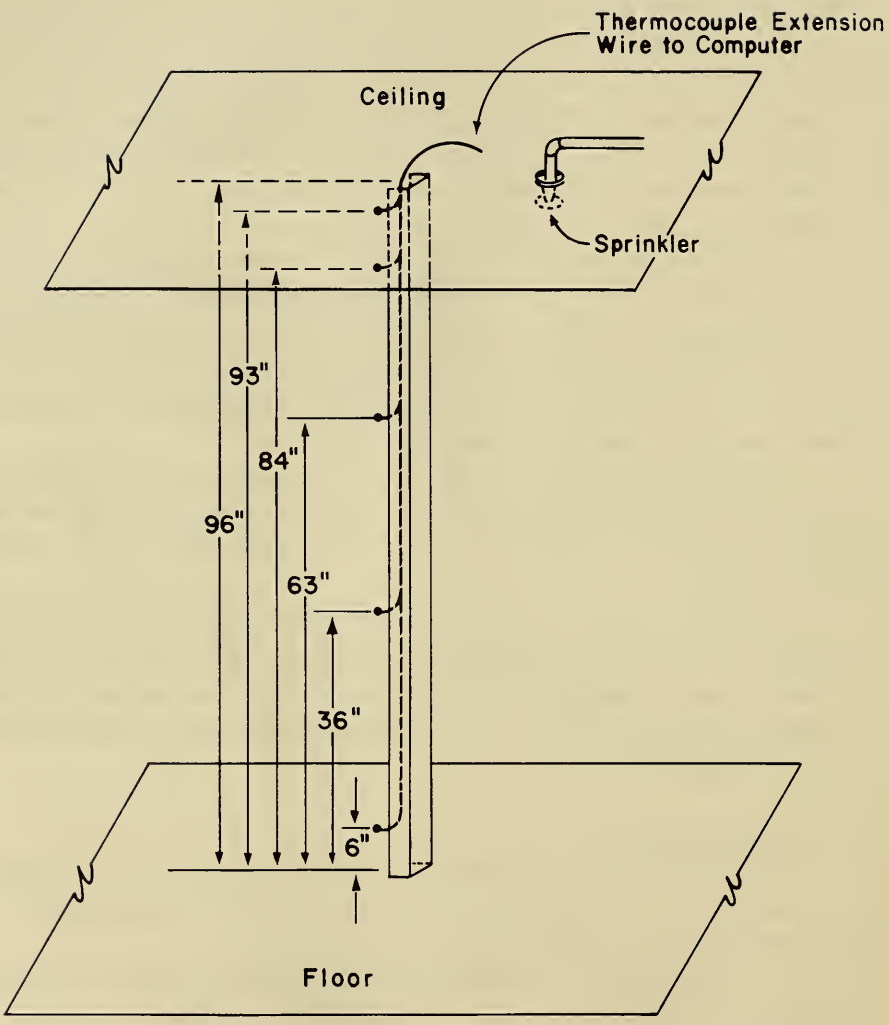


FIGURE 12 THERMOCOUPLE TREE SHIELDED WITH "UNISTRUT" CHANNEL

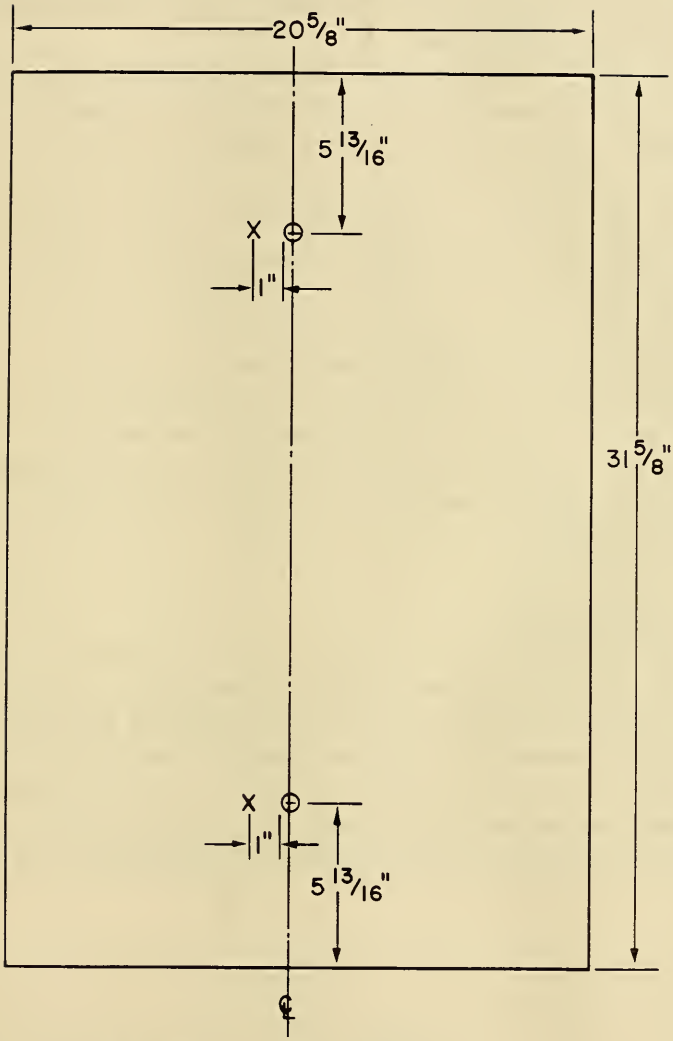


FIGURE 13 NORTHWEST WINDOW INSTRUMENTATION LOCATIONS

2) gas temperatures at two locations in the northwest window (see Figure 13) and two locations in the entry doorway, 55 in. and 70 in. above the floor (see Figure 14).

In Tests S2.2 and S2.3 brass sensing disks were used to simulate sprinkler links of various sensitivities. Each disk was fabricated from brass shim stock. The diameter of all disks was 3/8 in. Three disk thicknesses were used; 0.032 in., 0.020 in. and 0.011 in. with corresponding time constants of 16.9 sec, 11.2 sec and 7.4 sec. The thermocouple bead, made from 30-gage inconel sheathed thermocouple wire, was spot welded to each disk (see Figure 15). In Test S2.3: 1) three disks with time constants of 16.9 sec, 11.2 sec, and 7.4 sec were installed near the first sprinkler (see Figure 16); 2) one disk with a time constant of 16.9 sec was installed near the second sprinkler (see Figure 17); and 3) one disk with a time constant of 16.9 sec was installed in the hallway (see Figure 18). In Test S2.2 the two disks with time constants of 16.9 sec near each sprinkler were not installed (see Figure 19 for disk arrangement near first sprinkler). The front surface of all disks installed in the test building faced toward the north.

3.3.3 Test Series 3

The instrumentation used in Test S3.1 was the same as that used in Test S2.2.

The instrumentation used in Test S3.2 was similar to that used in Test S2.3; a gas velocity measurement near the second sprinkler was added.

For the remainder of the tests in Series 3 (S3.3-S3.8) the instrumentation was similar to that of Test S3.2. In addition, four gas temperature measurements were made, two located in the kitchen (93 in. and 63 in. above the floor) and two located in the hallway, 93 in. and 63 in. above the floor (see Figure 20).

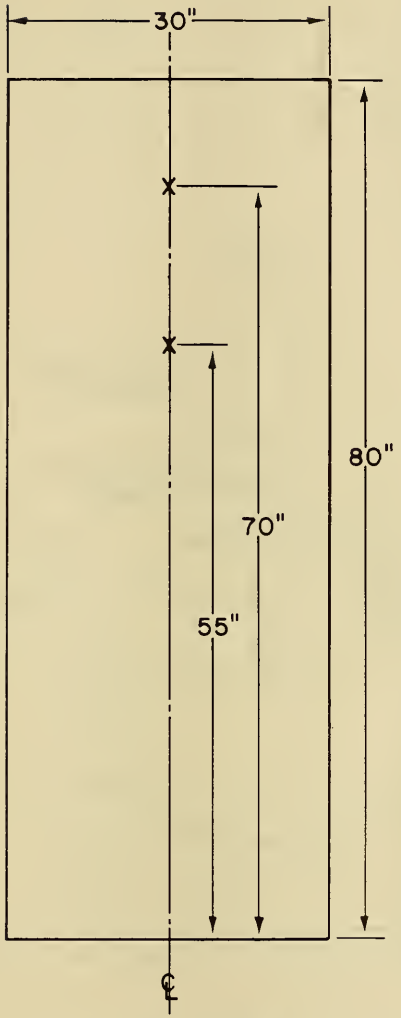


FIGURE 14 ENTRY DOORWAY INSTRUMENTATION LOCATIONS

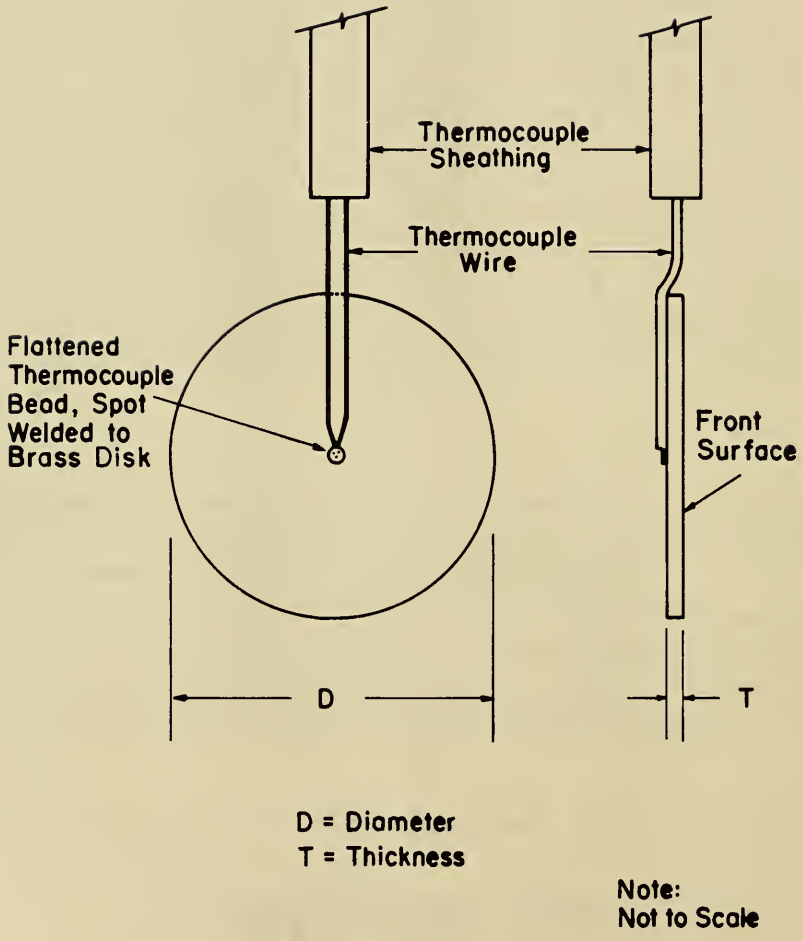


FIGURE 15 SIMULATED SPRINKLER LINK

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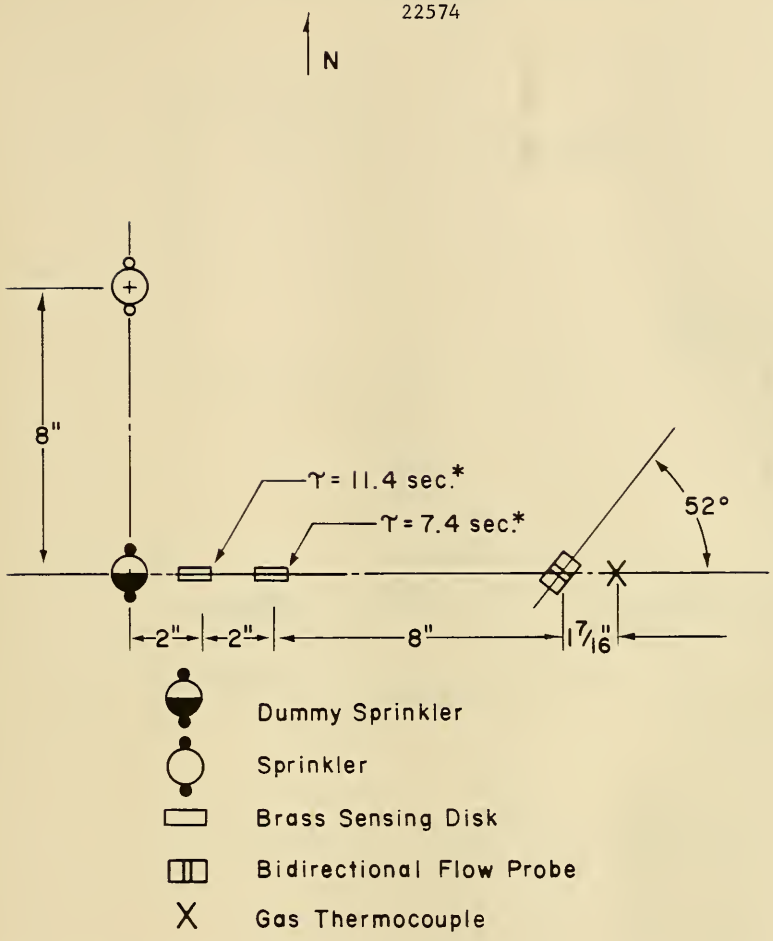
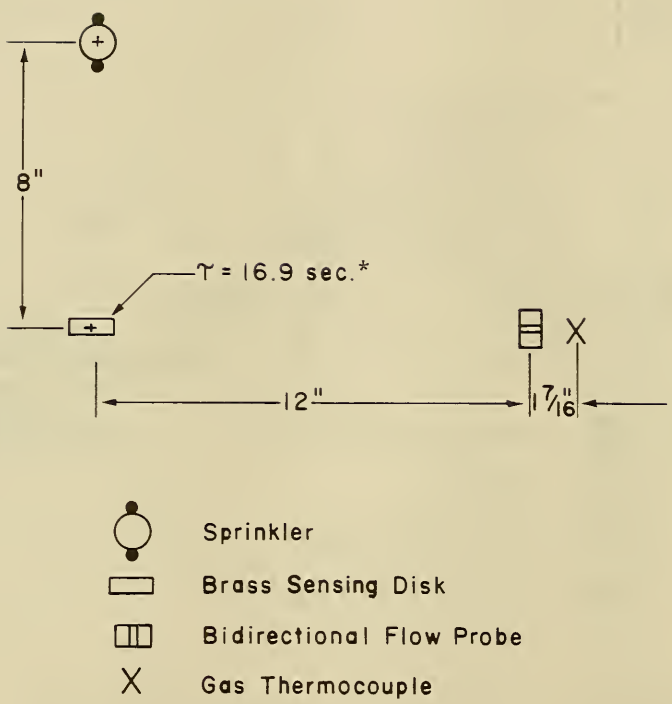


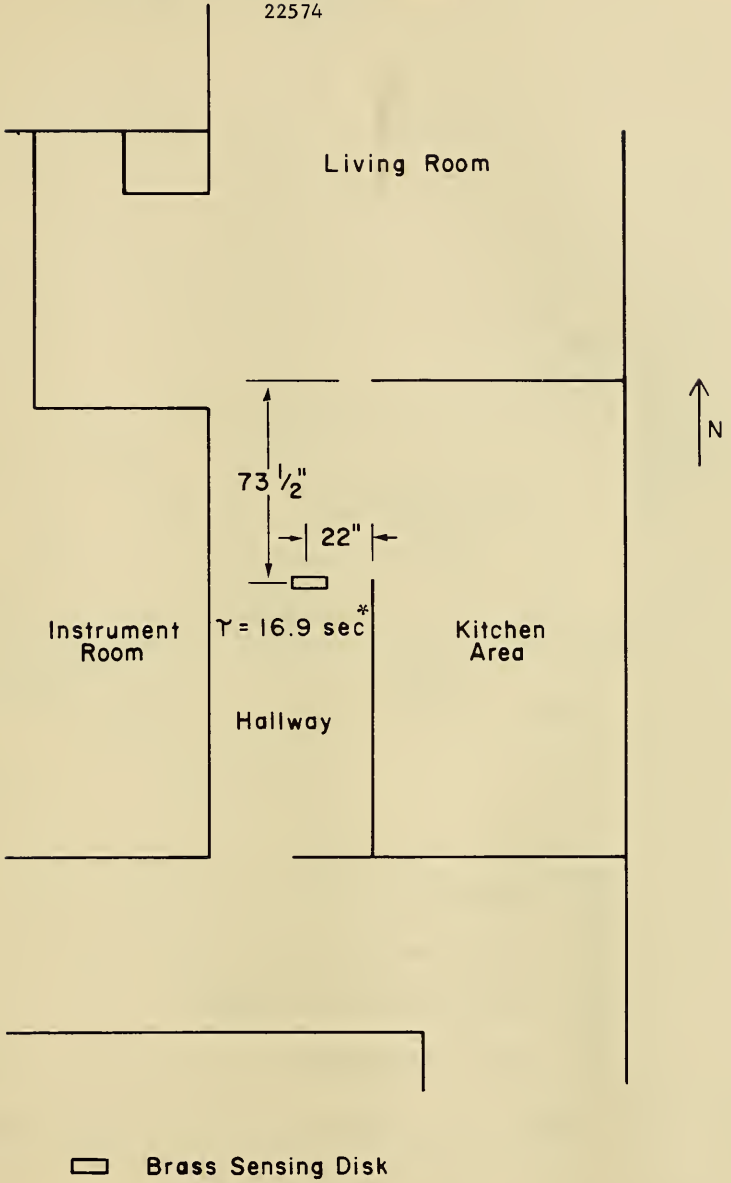
* Note: Time Constant (τ) was measured at a velocity of 7.4 ft/sec

FIGURE 16 INSTRUMENT LOCATIONS ADJACENT TO SPRINKLER NO.1 FOR TESTS S2.2 AND S3.1



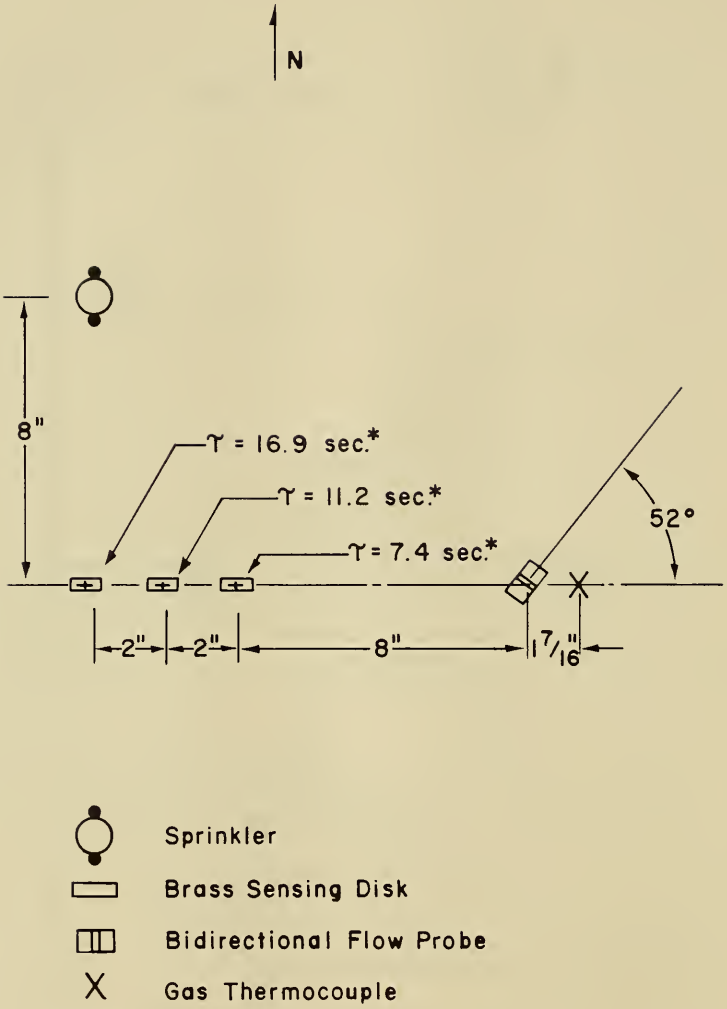
* Note: Time Constant (τ) was measured at a velocity of 7.4 ft/sec

FIGURE 17 INSTRUMENT LOCATIONS ADJACENT TO SPRINKLER NO.2 FOR TESTS S2.3,S3.2-S3.7



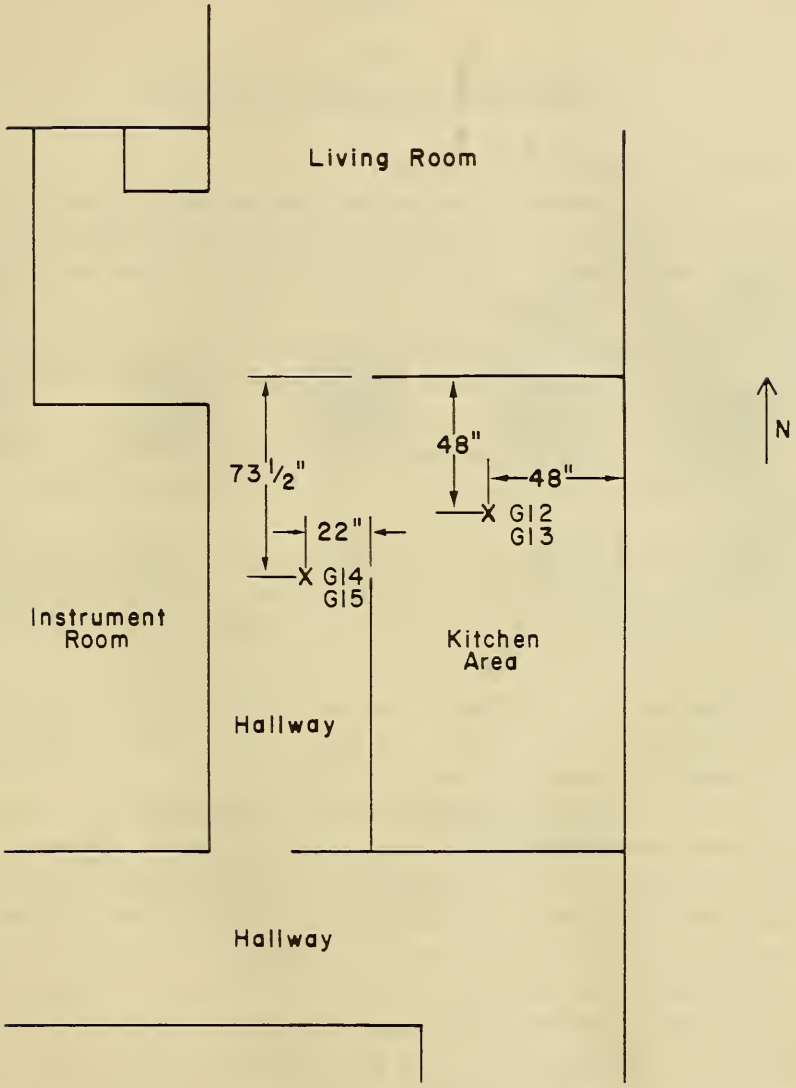
* Note: Time Constant (τ) was measured at a velocity of 7.4 ft/sec

FIGURE 18 SENSING DISK LOCATION IN HALLWAY



* Note: Time Constant (τ) was measured at a velocity of 7.4 ft/sec

FIGURE 19 INSTRUMENT LOCATIONS ADJACENT TO SPRINKLER NO.1 FOR TESTS S2.3,S3.2 AND S3.7



X Gas Thermocouple

G12, G14 Elev = 93"

G13, G15 Elev = 63"

FIGURE 20 THERMOCOUPLE LOCATIONS IN HALLWAY AND KITCHEN

IV
TEST SPRINKLERS AND WATER DISTRIBUTION

4.1 SPRINKLER AND WATER SUPPLY SYSTEMS

Five different types of sprinklers were used as water-discharge devices: 1) commercial 5/16-in. orifice sprinkler; 2) experimental 0.275-in. orifice sprinkler; 3) experimental 0.329-in. orifice sprinkler; 4) manufacturer's prototype 1; and 5) manufacturer's prototype 2. Figure 21 is a photograph of the five sprinklers. Only the two manufacturer's prototype sprinklers were equipped with both a sprinkler valve assembly and a link-lever releasing device. The others were open sprinklers.

The two different-sized experimental sprinklers are geometrically similar. The detailed dimensions of the 0.329-in. orifice sprinklers are shown in Figure 8 of Ref 4.

For the bedroom and the small-bedroom fire tests, a test sprinkler was mounted at the center of the ceiling within the room. For the living room fire tests, two test sprinklers were mounted at the ceiling of the living-dining area. The sprinkler deflector was positioned 3 in. below the ceiling and the plane of the supporting arms for the deflector was perpendicular to the north wall. The sprinkler locations for the bedroom, the small bedroom, and the living room fire tests are shown in Figures 3, 4, and 5 respectively.

When open sprinklers were used in the tests, the water flow to each open sprinkler was controlled individually by a solenoid valve in the water line immediately upstream of the test sprinkler. In several tests, a commercial sprinkler with a relatively fast responding link (time constant; 73.9 sec) was installed 8 in. south of each sprinkler (Figures 3, 4, and 5). The commercial sprinklers (not connected to a water line) were used to activate water flow to the open sprinklers. Each "dummy" commercial sprinkler was electrically connected to the solenoid valve of the open sprinkler adjacent to the "dummy" sprinkler. When the thermal link fused, it acted as an electric switch opening the solenoid valve, causing the water flow.

In five tests, 3/8-in. diameter, 0.032-in. thick brass disks (time constant, 16.9 sec) were used to simulate the sprinkler links for flow activation to the test sprinklers. Inconel sheathed, 30-gage (B&S) iron-constantan thermocouple

(1) commercial 5/16-in.-orifice sprinkler
(2) experimental 0.275-in.-orifice sprinkler
(3) experimental 0.329-in.-orifice sprinkler
(4) manufacturer's prototype #1
(5) manufacturer's prototype #2

FIGURE 21 PHOTOGRAPHIC VIEW OF TEST SPRINKLERS

wire was welded to the disk. The disk was hung from the ceiling attached to the thermocouple wire, 8 in. south of each test sprinkler parallel to the north wall. The distance between the ceiling and the center of the disk was 2 1/2 in. Each pair of thermocouple wires welded to the disks was connected to a temperature controller (LFE Model 232). The controller was wired to a solenoid valve upstream of each test sprinkler. Prior to a test, the temperature controller was set at a predetermined temperature. During a test, the temperature of the disk rose to this preset temperature and tripped the temperature controller which in turn acted as an electrical switch, opening the solenoid valve.

In tests using manufacturer's prototype sprinklers, normal sprinkler activations were achieved by the link mounted on the sprinkler frame.

The water for each test sprinkler was supplied by 1-in. steel pipe branched from a 2-in. main pipe; see Figure 22.

Water was pumped from a storage tank, and water flow rates were measured, using a rotameter (Schutte & Koerting Instruments; full range 0-25 gpm).

Before the tests with open sprinklers, the flow rate for the first sprinkler was set by opening the solenoid valve and adjusting the valve located at the rotameter with the pump running. The solenoid valve was then closed.

For the tests with manufacturer's prototype sprinklers, the flow rate for the first sprinkler was set by using an open sprinkler of the same kind. Then the solenoid valve was closed and a linked prototype sprinkler was installed, replacing the open sprinkler; the solenoid valve was subsequently left open throughout the entire test period.

For the living room fire tests, at the time of second sprinkler activation, the total flow rate was increased to a predetermined setting by adjusting the valve located at the rotameter.

4.2 SPRINKLER WATER DISTRIBUTION

In order to investigate the effect of sprinkler water distribution on sprinkler performance in the fire tests, water distributions on floor and walls were measured for the sprinkler discharge conditions employed in the test program (with the exception of the discharge condition in the small bedroom fire). Since each of the sprinklers was symmetrical with respect to the plane of the supporting

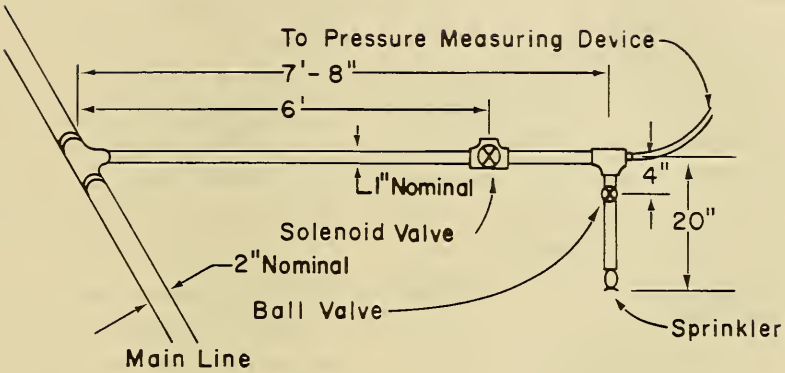


FIGURE 22 SCHEMATIC DRAWING OF 1-INCH BRANCH LINE OF THE SPRINKLER SYSTEM

arms of the deflector and also with respect to the orthogonal plane, only the water distribution of a quarter of the sprinkler spray bounded by these two planes was measured.

Water distribution measurements were conducted in the FMRC Hydraulic Laboratory. For the measurement of water distribution on the floor, 64 square water-collection pans, each having a collection area of 1 ft x 1 ft, were arranged in a square matrix of 8 x 8 pans on the floor with pans touching. The outline of the matrix of the collection pans relative to the sprinkler position is shown in Figure 23a. A 4-ft x 4-ft ceiling was installed 8 ft above the level of the top edges of the pans, below an existing 10-ft x 12-ft ceiling. (Note that the ceiling height in the fire test building is also 8 ft.) The sprinkler was installed at the center of the 4-ft x 4-ft ceiling with the deflector 3 in. below the ceiling and with the plane of the supporting arms parallel to one side of the matrix of the collection pans. A front view of this setup is shown in Figure 23b. Water collected in each pan over a period of time (3 min to 15 min) was measured in a graduated cylinder.

After completion of the floor water distribution measurements, all 64 pans were removed and the vertical water distributions were measured at three positions on each of the two vertical planes 6 ft from the sprinkler (see Figure 24). Three racks of collection pans were fabricated, each rack consisting of eight pans. Rack B in Figure 24 corresponds to the wall region behind the right arm of the chair where initial intense burning occurred in the living room fire tests. Each pan has a 1-ft wide x 1/2-ft high vertical collection area; Figure 25 provides the pan dimensions. The arrangement of the eight pans on a rack with the bottom pan positioned on the floor is shown in Figure 26. The distance between any two adjacent collection surfaces was 6 in. The elevation of the ceiling above the bottom edge of the bottom collection area was 7 ft 11 in. Measurements were first made with three racks placed on one plane, the bottom pans resting on the floor as in Figure 26. Then all the pans were moved up 6 in. to measure the water densities of the 1-ft x 1/2-ft gap areas initially not included. The procedure was then repeated on the othogonal plane.

Figures 27-34 present the floor and vertical water distribution data of the commercial 5/16-in. sprinkler operating at 6 and 9 gpm, the experimental 0.275-in.

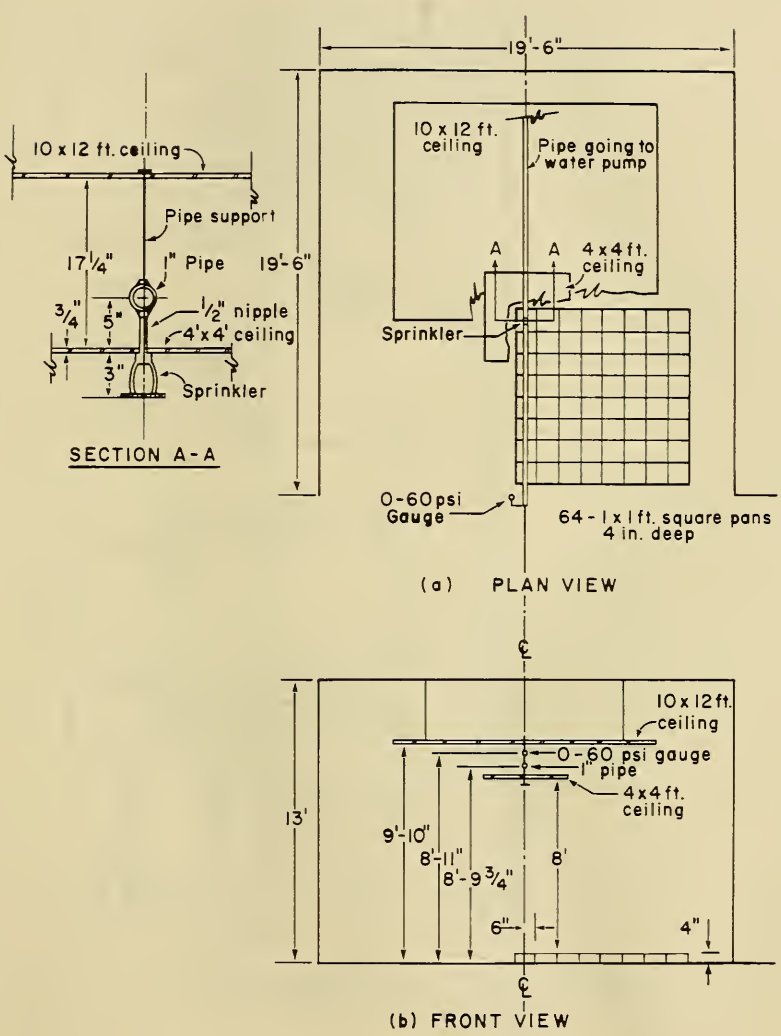
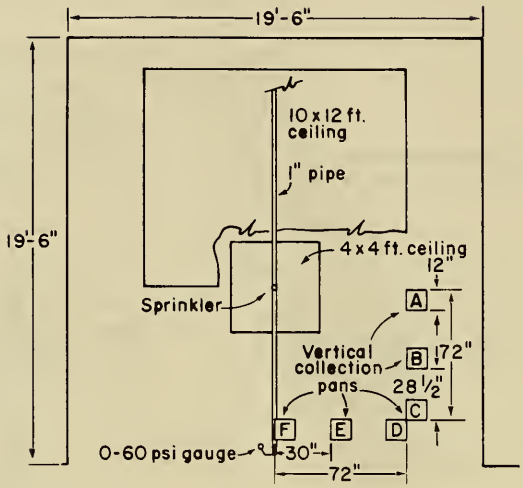
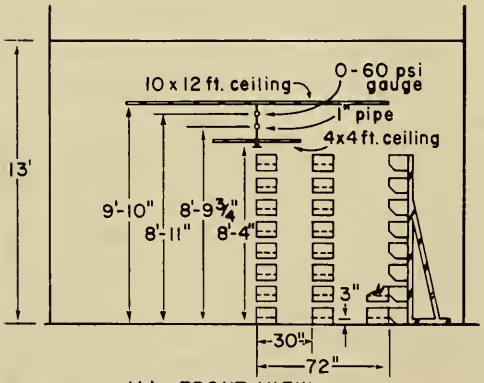


FIGURE 23 PLAN VIEW AND FRONT VIEW OF SETUP FOR FLOOR WATER DISTRIBUTION MEASUREMENT



(a) PLAN VIEW



(b) FRONT VIEW

FIGURE 24 PLAN VIEW AND FRONT VIEW OF SETUP FOR VERTICAL WATER DISTRIBUTION MEASUREMENT

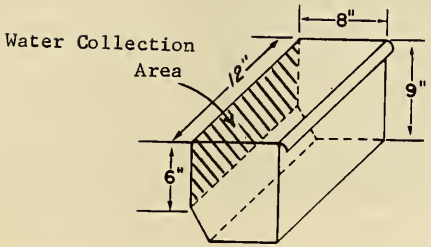


FIGURE 25 WATER COLLECTION PAN

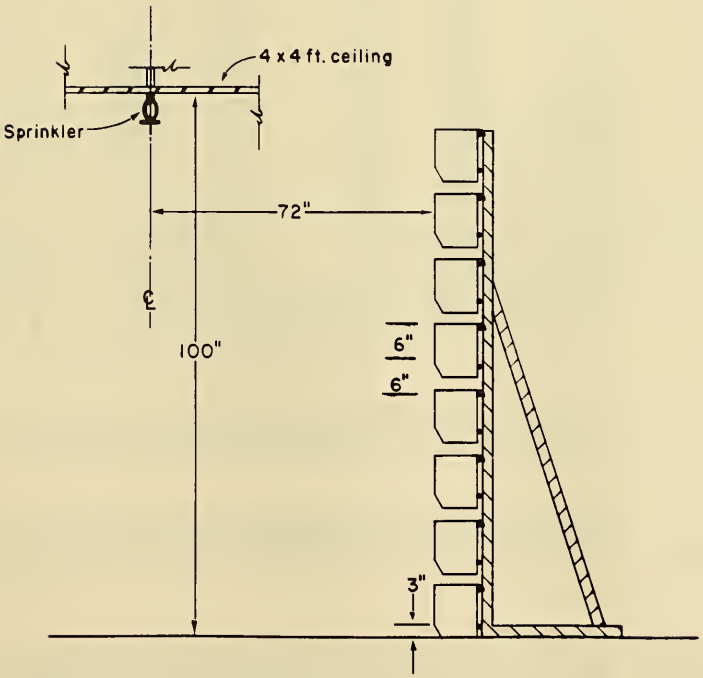


FIGURE 26 VERTICAL DISTRIBUTION RACK

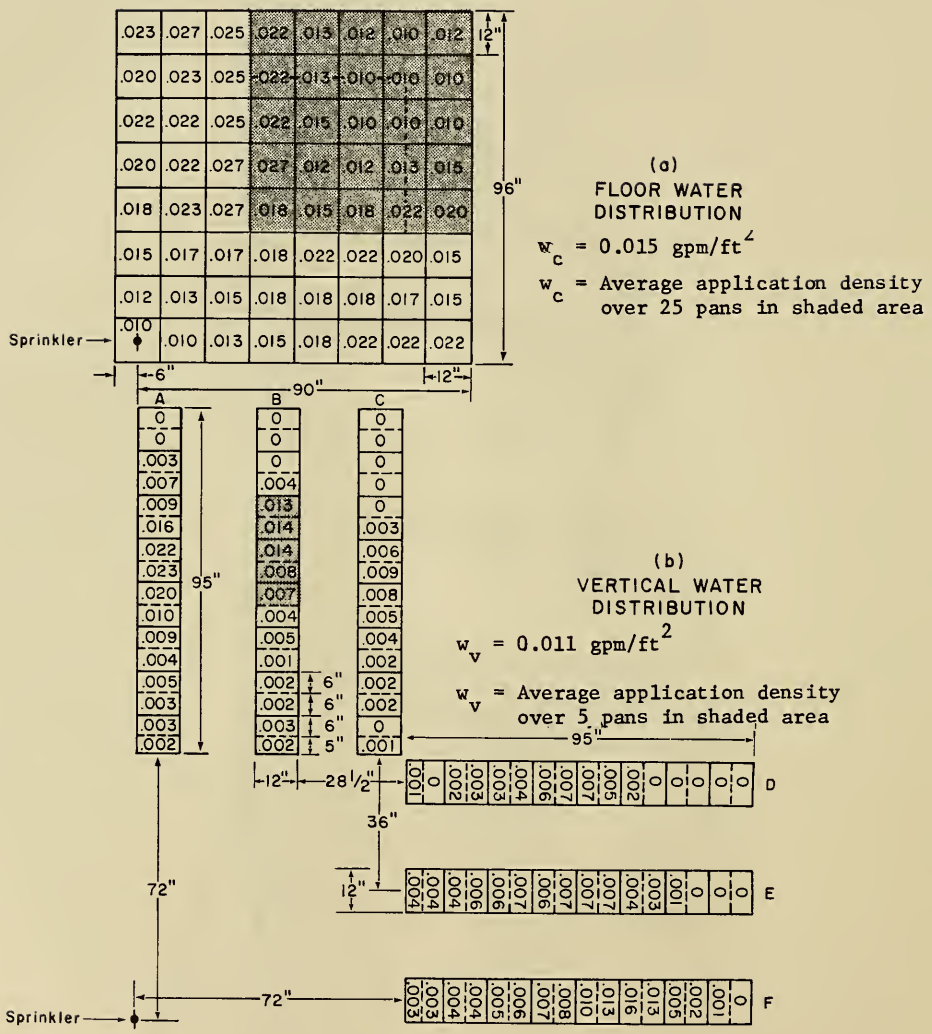


FIGURE 27 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Commercial 5/16-in. Orifice Sprinkler, K=2.01, 6gpm, 9psig, For Tests S1.3,S2.1,S2.3

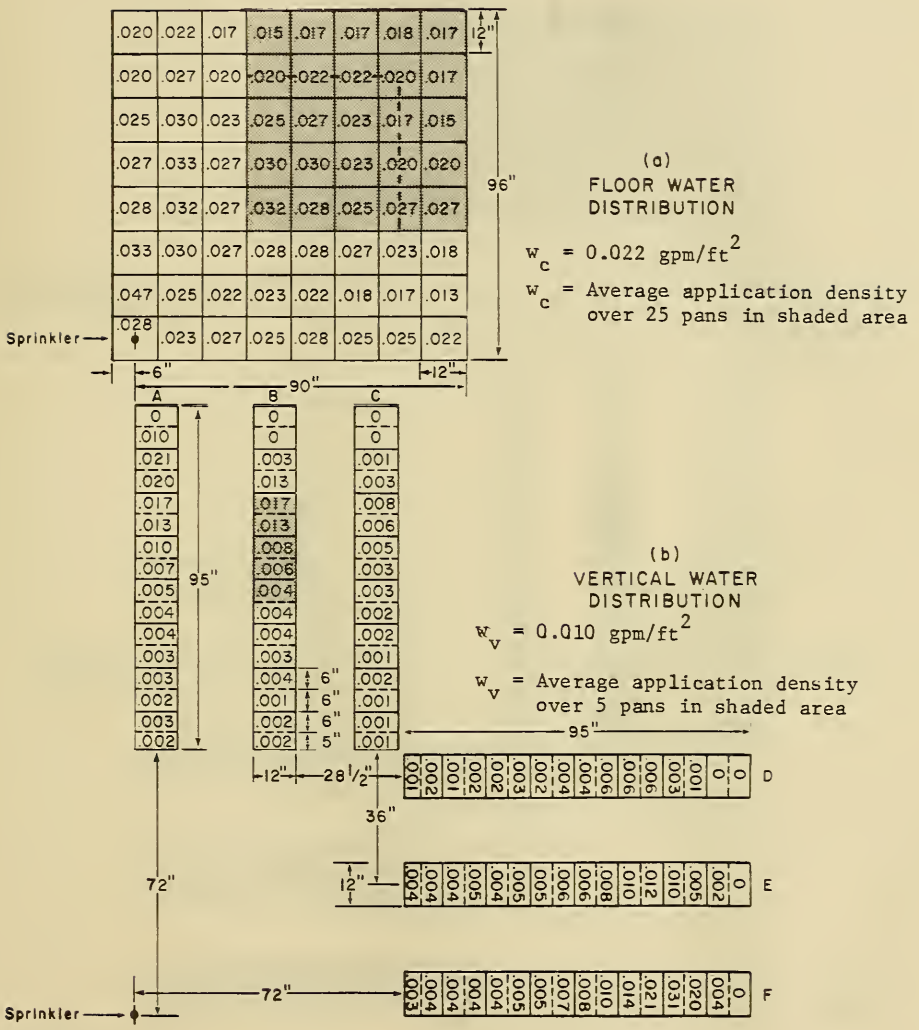


FIGURE 28 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Commercial 5/16-in. Orifice Sprinkler, K=2.12, 9gpm, 18.0psig, For Test S2.2

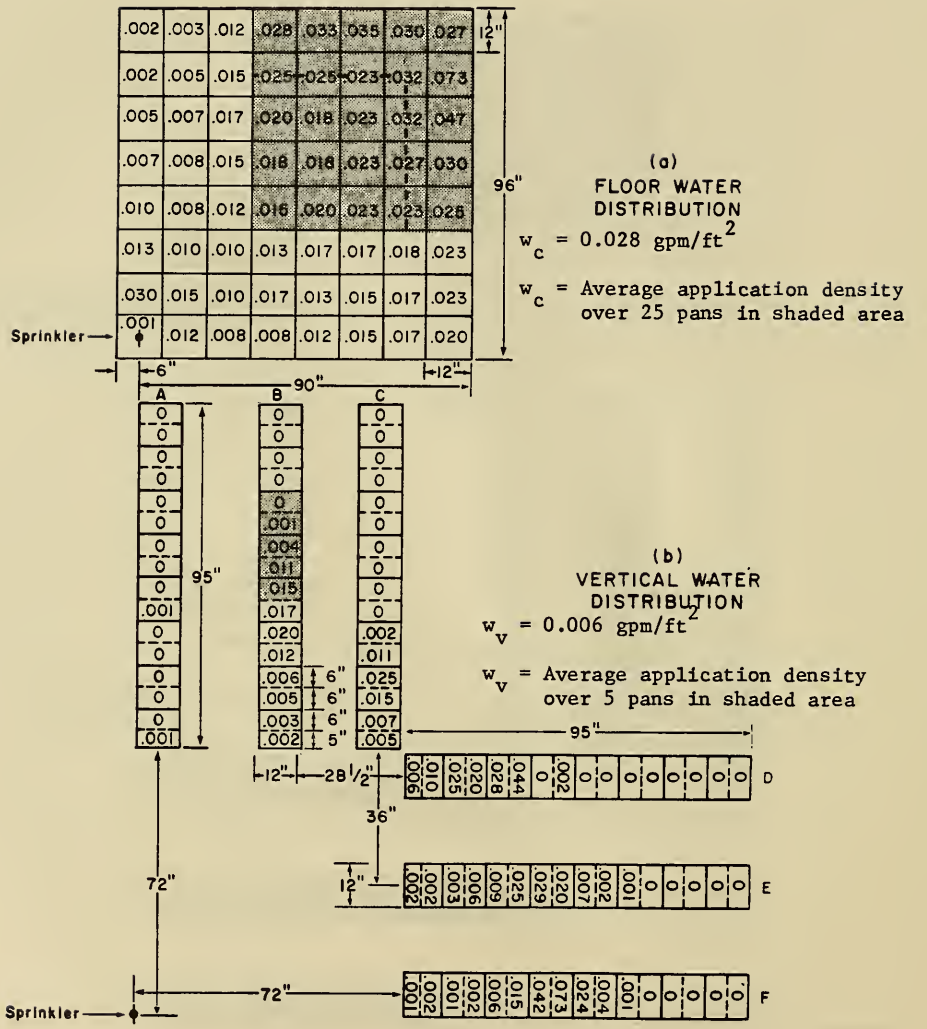


FIGURE 29 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Experimental 0.274-in. Orifice Sprinkler, K=2.12, 9 gpm, 20.7psig, For Tests S3.1, S3.2

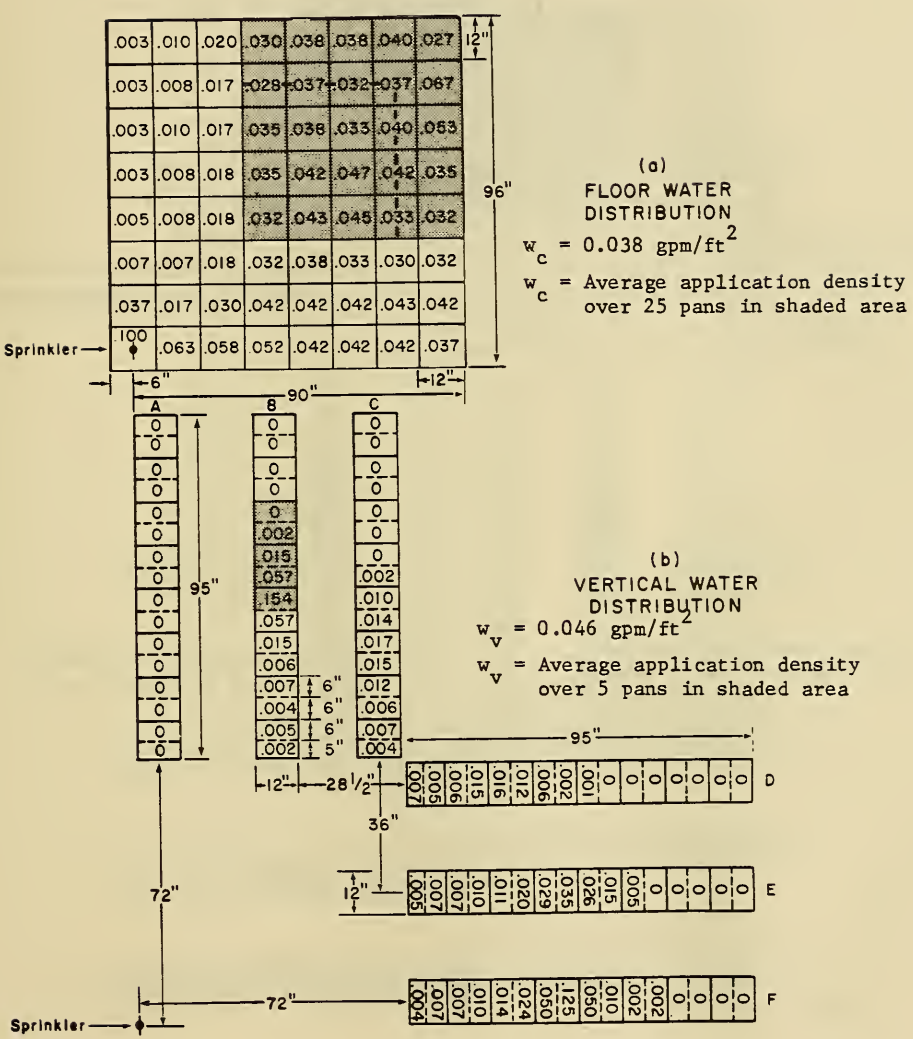


FIGURE 30 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Experimental 0.329-in. Orifice Sprinkler K=3.11, 12gpm, 16.2psig, For Tests S3.3, S3.4

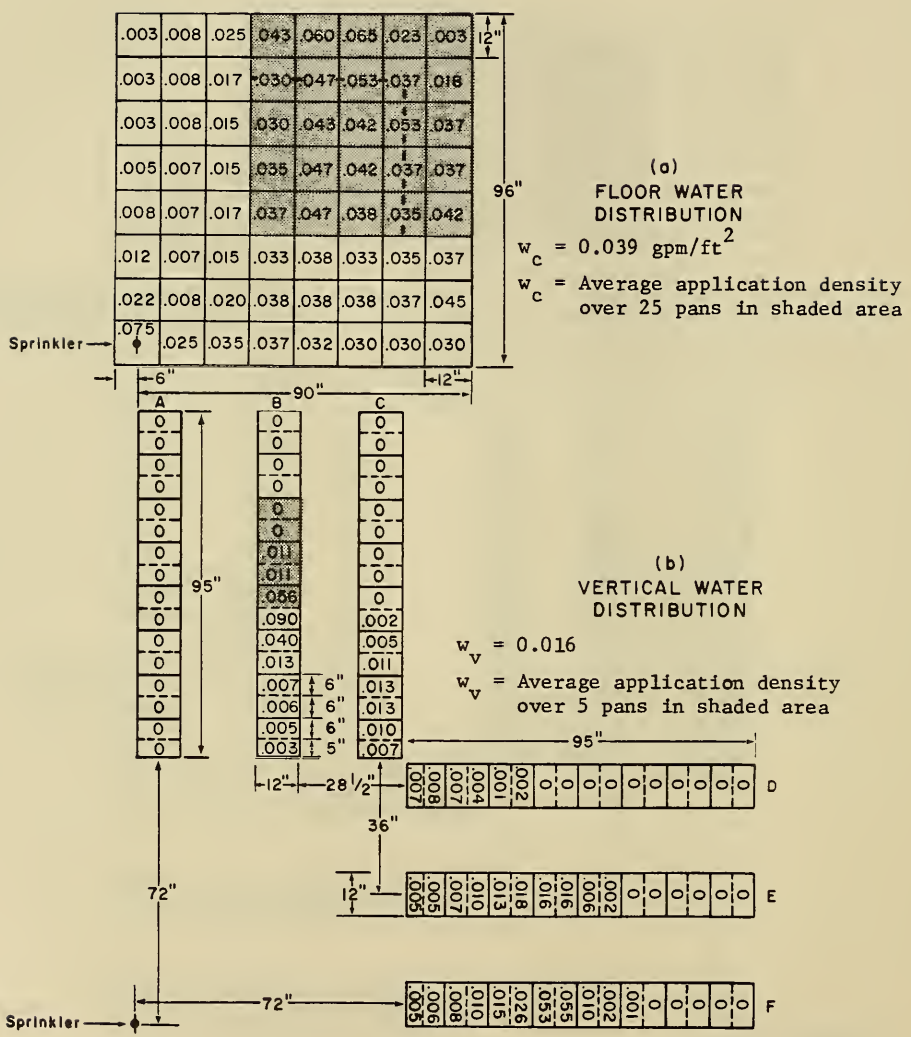


FIGURE 31 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Experimental 0.329-in. Orifice Sprinkler, K=3.11, 9gpm, 9.2psig, For Tests S3.3, S3.4

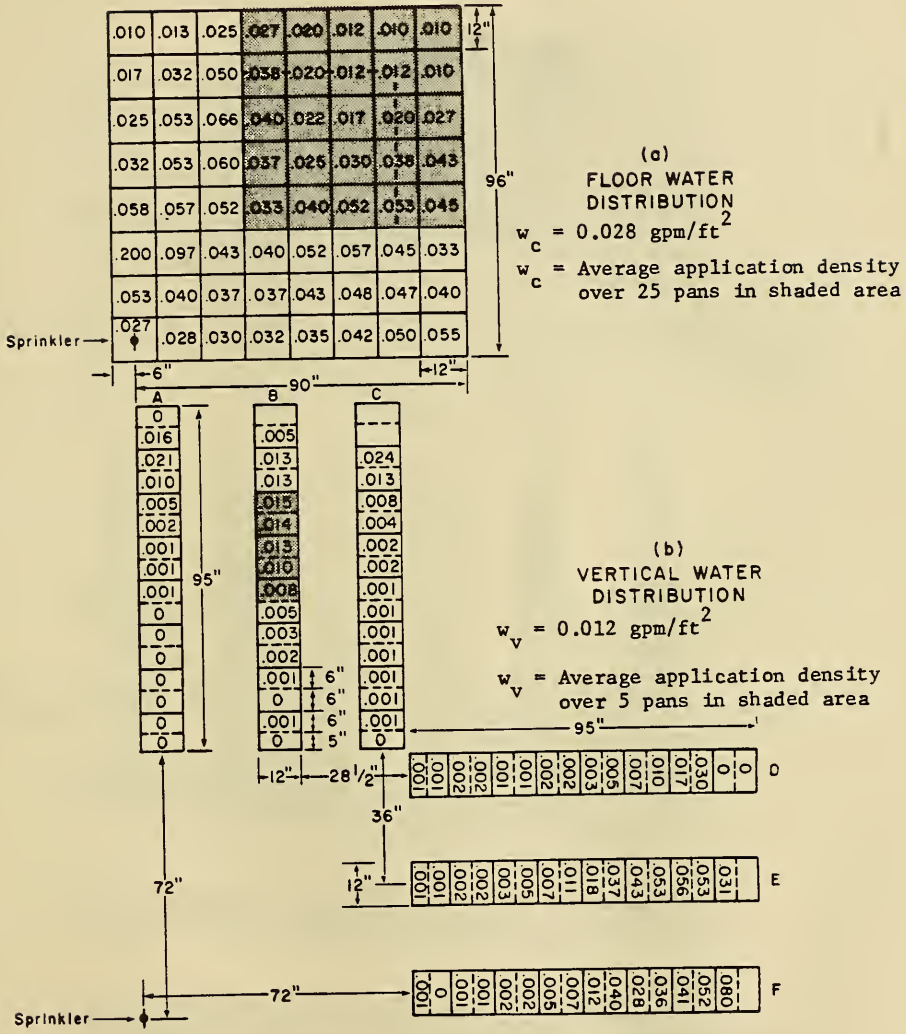


FIGURE 32 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Manufacturer's Prototype No. 1, K=2.69, 12gpm, 19.9psig, For Test S3.5

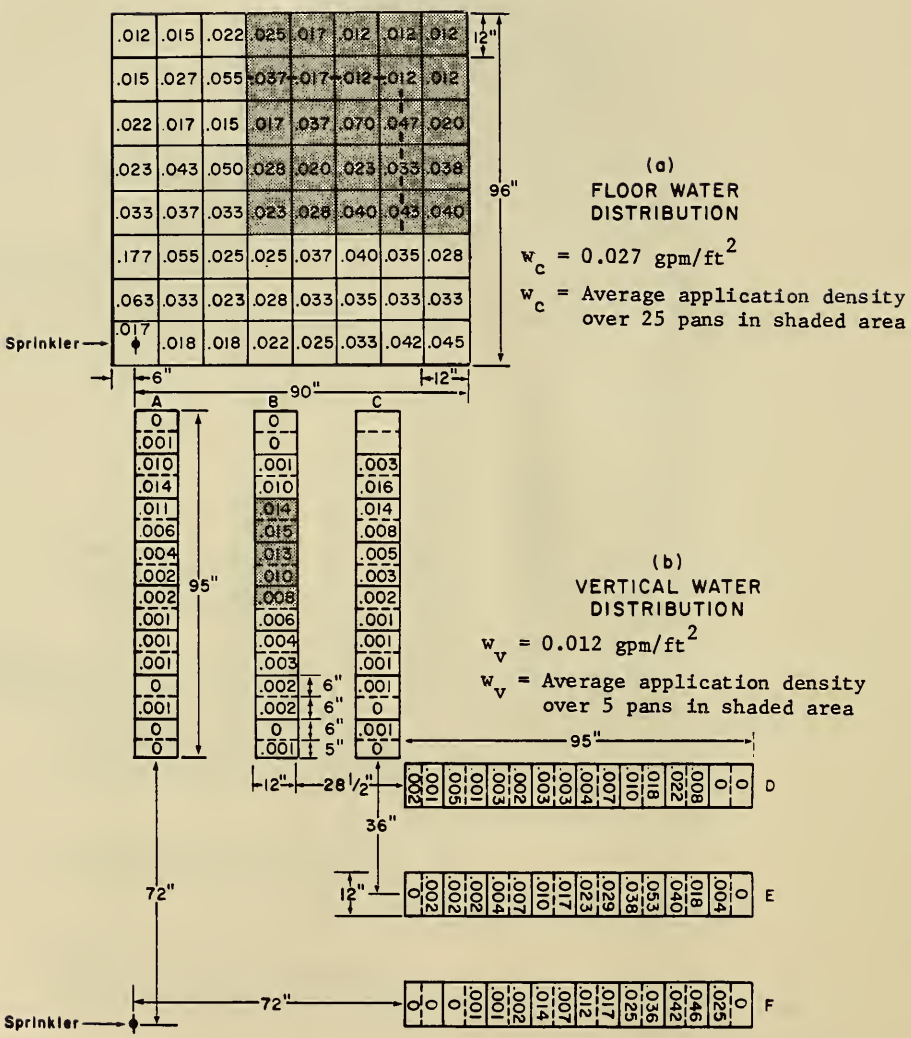


FIGURE 33 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Manufacturer's Prototype No. 1, K=2.69, 9gpm, 11psig, For Test S3.5

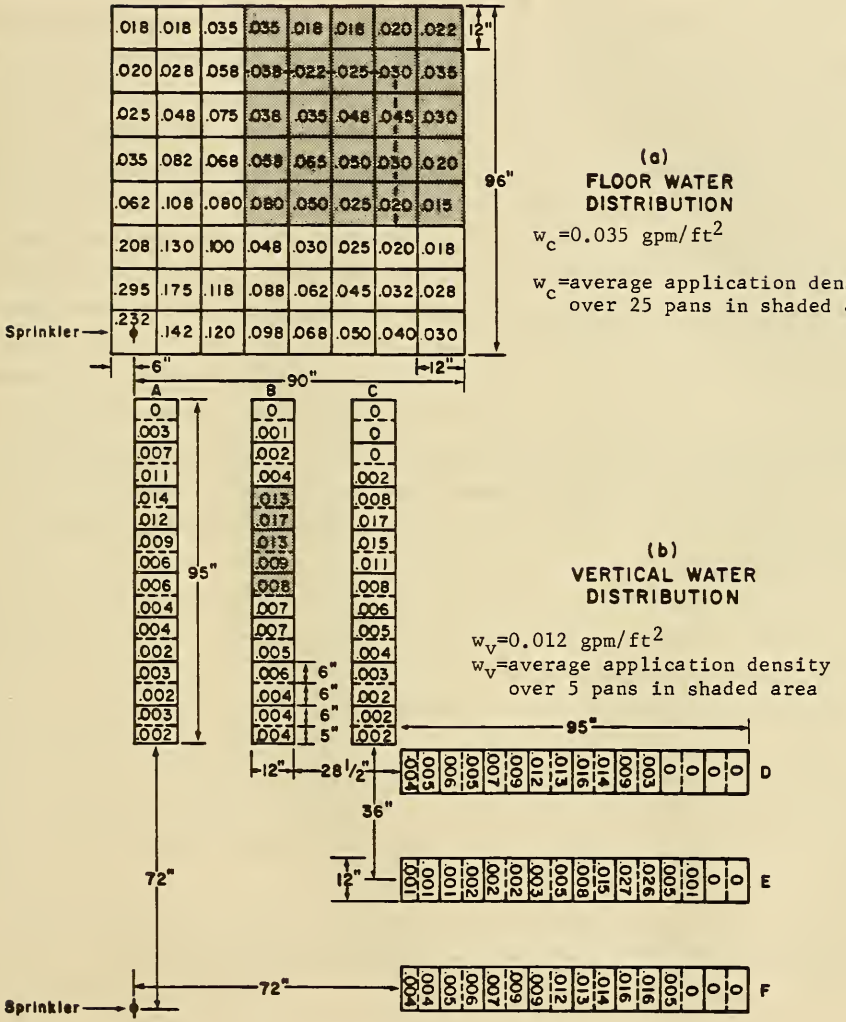


FIGURE 34 FLOOR AND VERTICAL WATER DISTRIBUTION MEASUREMENTS: Manufacturer's Prototype No.2, K=3.00, 15gpm, 25psig, For Tests S3.6 and S3.7

sprinkler at 9 gpm, the experimental 0.329-in. sprinkler at 12 and 9 gpm, the manufacturer's prototype 1 at 12 and 9 gpm, and the manufacturer's prototype 2 at 15 gpm.

The average water application density, w_c, over the 25 pans represented by the shaded area in the floor water distribution plan (Figures 27 to 34) is used as an indicator of the amount of sprinkler water reaching the fire source in the corner of the living room. The outer edges of the shaded area were 7.5 ft from the centerline of the sprinkler. In the actual living room fire tests, the east and north walls of the living room were 6 ft from the sprinkler, as indicated by the dashed corner in Figures 27 to 34. The water collection reported outside the dashed corner in Figures 27 to 34 is an indicator of the amount of water which would have hit the lower portion of the walls if walls had been present during these water distribution measurements.

If walls had been present, water collected over the 1-ft x 2.5-ft shaded area of Rack B in the vertical water distribution plan of Figures 27 to 34 would have dripped along the plywood panel behind the chair, affecting ignition of the walls in the living room fires. The vertical application density, w_v, over the 1-ft x 2.5-ft shaded area indicates the amount of water delivered to protect the wall.

V

TEST PROCEDURE AND OBSERVATIONS

5.1 TEST PROCEDURE

A residential sprinkler system is intended to maintain a survivable environment within the fire room for a limited period of time, sufficient for occupants to be rescued (or possibly to escape). A period of 15 min after sprinkler operation appears reasonable. Therefore, all tests were conducted for a period from time of ignition to at least 15 min after first sprinkler operation.

Prior to each test, all thermocouples were checked; micromanometers were calibrated and set; the optical density meter was checked; and the CO, CO_2, and O_2 analyzers were calibrated and set. Weather conditions were noted: the wind condition, inside and outside air temperatures, and inside and outside relative humidity (see Table VII).

Before each test, the flow rate for the first sprinkler operation was set. In the living room fire test, at the time of second sprinkler activation the total flow rate was increased to a predetermined rate (see Section 4.1).

The ignition source for the bedroom fire (Test S1.1) and the small-bedroom fire (Test S1.2) was a full sheet of newspaper rolled up into a ball and placed on the floor under the side of the bed (see Figures 3 and 4 respectively for ignition locations). The newspaper was then ignited by a match. For all living room fire tests, ignition was accomplished by an electric match placed through a hole on the side of a plastic wastebasket 1 in. up from the bottom. The electric match was placed near three full sheets of newspaper, each rolled into a ball, that were placed in the basket. Above the rolled newspapers were four bundles, each consisting of seven full sheets of newspaper folded in half three times. The electric match was powered by 120 V/ac through a manually operated switch.

Color video tapes of all tests were taken; the camera was located behind a tempered glass observation window in a partition wall. In some tests 35-mm color slides were also taken.

TABLE VII

PRETEST WEATHER CONDITIONS

Test No.	Wind (mph; dir)	Bar (in. Hg.)	Temp °F Outside	Temp °F Inside	Rel. Humidity % Outside	Rel. Humidity % Inside	Ventilation
S1.1	N/A	30.91	N/A	77	66	63	No
S1.2	N/A	N/A	N/A	71	N/A	81	No
S1.3	N/A	30.05	N/A	86	61	N/A	No
S2.1	N/A	N/A	N/A	63	N/A	39	Yes
S2.2	SSW	29.57	40	56	92	71	Yes
S2.3	14 WSW	29.80	46	55	73	N/A	Yes
S3.1	12 WNW	30.38	45	62	53	N/A	Yes
S3.2	13 NW	29.91	33	44	35	N/A	Yes
S3.3	16 SSW	30.34	47	57	67	57	Yes
S3.4	10 N	29.71	43	54	82	74	Yes
S3.5	10 NW	29.70	48	55	63	N/A	Yes
S3.6	21 E	29.74	39	54	85	85	Yes
S3.7	11 E	30.18	65	70	75	77	Yes

N/A - Not Available

5.2 OBSERVATIONS

A log of visual observations and damage assessments are presented for each of the fire tests in Appendix A. Pictorial histories prior to sprinkler operation of a selected number of fire tests are also presented in Appendix A; these pictures were taken from video tapes accompanying the observations. Post-test appearances of some of the tests are also shown in Appendix A.

For the living room fire test S3.5 (Table A.11), a carpet of the same material was used as in the other tests but without the foam backing. As a result, it took approximately 5 min longer than in the other tests for the fire to reach the left side of the vinyl chair.

VI
RESULTS AND DISCUSSION

To evaluate the adequacy of life-safety protection provided by sprinklers, measurements were made of CO, CO_2 and O_2 gas concentrations and gas temperature at eye level in the room of fire origin. The ability of residential sprinklers to provide property protection was assessed by measurement of the ceiling surface temperature over the fire source.

During ventilated living room fire tests, gas temperatures and gas velocity at the northwest window were monitored continuously during each test. Gas temperature measurements in the window were also used to evaluate the potential of fire spread to the exterior structure, while gas temperature measurements in the entrance door were employed to assess the likelihood of fire spread to the rest of the building.

In Tests S3.3 through S3.8 of Test Series 3, additional gas temperatures were measured at eye level in the kitchen and in the hallway to evaluate escape potential along the egress route.

Sprinkler response time with known link sensitivity and temperature rating can be predicted theoretically by means of gas temperature and velocity histories at the sprinkler. Measurements of gas temperature and velocity in the vicinity of the sprinkler closest to the fire source were used to aid in the selection of a sprinkler link with a sensitivity such that, at the time of sprinkler activation, the fire would still be in the early stage of its rapid development. In Test Series 2 and 3, the thermal responses of simulated sprinkler disks with different sensitivities were measured to verify the theoretical predictions.

The sprinkler water distribution required to control residential fires has been determined from the fire test results, together with sprinkler water distribution measurements (Section 4.2).

6.1 LIFE SAFETY AND PROPERTY PROTECTION CRITERIA

6.1.1 Life Safety Criteria

Measurements of CO and gas temperature at eye level in the room of fire origin were employed to evaluate the adequacy of life safety protection provided by sprinklers.

Carbon monoxide has been identified as the major toxic gas in the fire environment causing fatality[5]. The primary toxic effect exerted by CO is to reduce the oxygen-carrying capacity of the blood. Once CO enters the body, it combines reversibly with the chief oxygen-carrying protein of the red blood cells, hemoglobin. This complex of CO and hemoglobin is termed "carboxyhemoglobin" (CO Hb); a 16-20 percent CO Hb saturation in venous blood will cause headache and an "abnormal visual evoked response."[10] The amount of CO Hb formation in the blood depends on the concentration and exposure duration. It is estimated[10] that a 43-min exposure at 1000 ppm, a 100-min exposure at 500 ppm, or a 400-min exposure at 200 ppm will result in a 20-percent CO Hb saturation in blood. Estimates of "hazardous levels" reported by Yuill[11] are 1,600 ppm for 1/2 hr, 800 ppm for 1-2 hr and 120 ppm for 8 hr. Kimmerle[12] reported that CO concentration at 1500 ppm will cause death after one hour of inhalation. A conservative criterion was selected for evaluating the CO hazard in the test program; the maximum CO concentration at eye level in the room of fire origin was required to be less than 1500 ppm throughout the entire test period, i.e., from the time of ignition to 15 min after sprinkler activation.

Inhalation of carbon dioxide rapidly leads to abnormal breathing. As little as 2 percent of CO_2 by volume in the inspired air effectively stimulates respiration and 3 percent doubles the lung ventilation. Inhalation of 7 to 10 percent CO_2 may be fatal within a short period.[13]

The normal oxygen content of air is 21 percent. Diminishing the supply of oxygen to 12 to 15 percent will result in shortness of breath, headache, dizziness and rapid fatigue. An oxygen supply of 6 to 8 percent will cause collapse, with the possibility of death.[12,13]

On the subject of human tolerance to heat, Kimmerle[12] reported that gas temperatures of more than 212°F in a fire environment were capable of causing loss of consciousness and death within several minutes. The criterion adopted for evaluating the heat hazard in the program was that the gas temperature at eye level should be less than 200°F throughout the test period.

6.1.2 Property Protection Criteria

Measurements of ceiling surface temperature over the fire source were used to assess the ability of residential sprinklers to provide property protection.

Cellulosic and plastic material usually begin to pyrolyze vigorously at a temperature of about 500°F.[14,15] The limit for the ceiling surface temperature directly above the ignition point is selected to be 500°F in order for sprinkler protection of property to be considered adequate.

6.2 TEST RESULTS

6.2.1 Test Series 1

This test series consists of three nonventilated fire tests: the bedroom fire (S1.1); the small-bedroom fire (S1.2); and the living room fire (S1.3). Gas concentrations of CO, CO_2 and O_2 at the 63-in. level near the center of the room are shown in Figures 35, 36, and 37. For the bedroom fire test, the maximum values of CO and CO_2 concentrations are 990 ppm and 1.7 percent respectively and the minimum oxygen concentration is 18.5 percent; whereas for the small-bedroom fire test, the maximum CO and CO_2 concentrations are 1107 ppm and 1.8 percent respectively, and the minimum O_2 concentration is 16.5 percent. For the living room fire test, the maximum CO concentration is 730 ppm, the maximum CO_2 concentration is 2.3 percent, and the minimum O_2 concentration is 18.4 percent. The CO and CO_2 concentrations and O_2 deficiency for these tests were smaller than the critical values.

Gas temperatures at three elevations, 93 in., 60 in., and 36 in. from the floor, are shown in Figures 38, 39, and 40. In the bedroom and small-bedroom fire tests, the gas temperatures measured at the three elevations reached maximum values at about the time of sprinkler activation (1 min, 57 sec for Test S1.1, and 2 min, 5 sec for Test S1.2). After sprinkler operation, the voltage readings from the thermocouples measuring these temperatures seemed to indicate that the thermocouple beads were wetted by the sprinkler spray.

From Figure 27, the water application density over the area of the fire source in the bedroom fire test is 0.02 gpm/ft^2. Based on the gas temperature results and the damage assessment after the test a 0.02 gpm/ft^2 local application density over the bed fire appears adequate.

In the bedroom fire test, the maximum eye-level gas temperature was 168°F. In the small-bedroom fire test, the eye-level gas temperature reached 241°F at the time of sprinkler activation. In such a small room, a more sensitive sprinkler link would have been required in order to activate the sprinkler before the eye-level gas temperature reached 200°F.

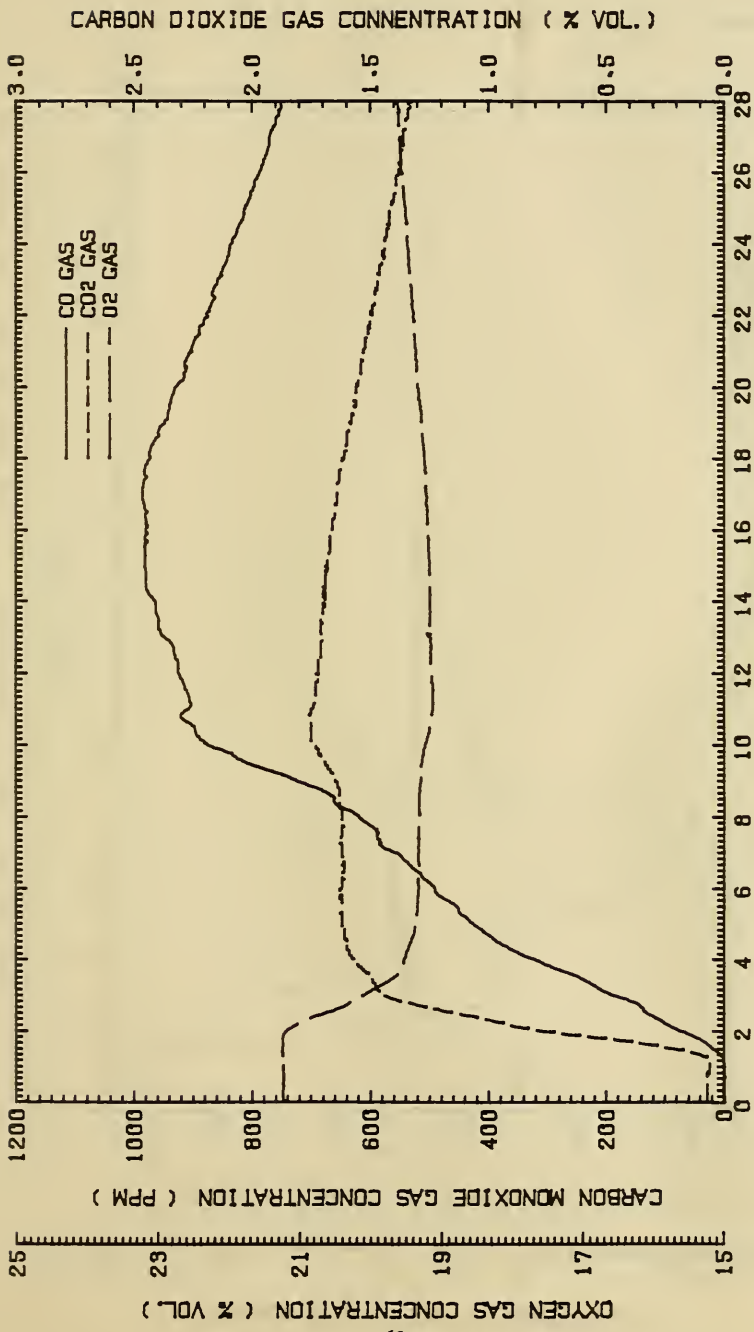

FACTORY MUTUAL RESEARCH CORPORATION
FMRC SERIAL NO. 22574
CARBON DIOXIDE GAS CONNENTRATION (% VOL.)
CO GAS
CO2 GAS
O2 GAS
TIME (MIN.)
CARBON MONOXIDE GAS CONCENTRATION (PPM)
OXYGEN GAS CONCENTRATION (% VOL.)

FIGURE 35 CO, CO_2 AND O_2 CONCENTRATIONS AT EYE LEVEL FOR TEST S1.1

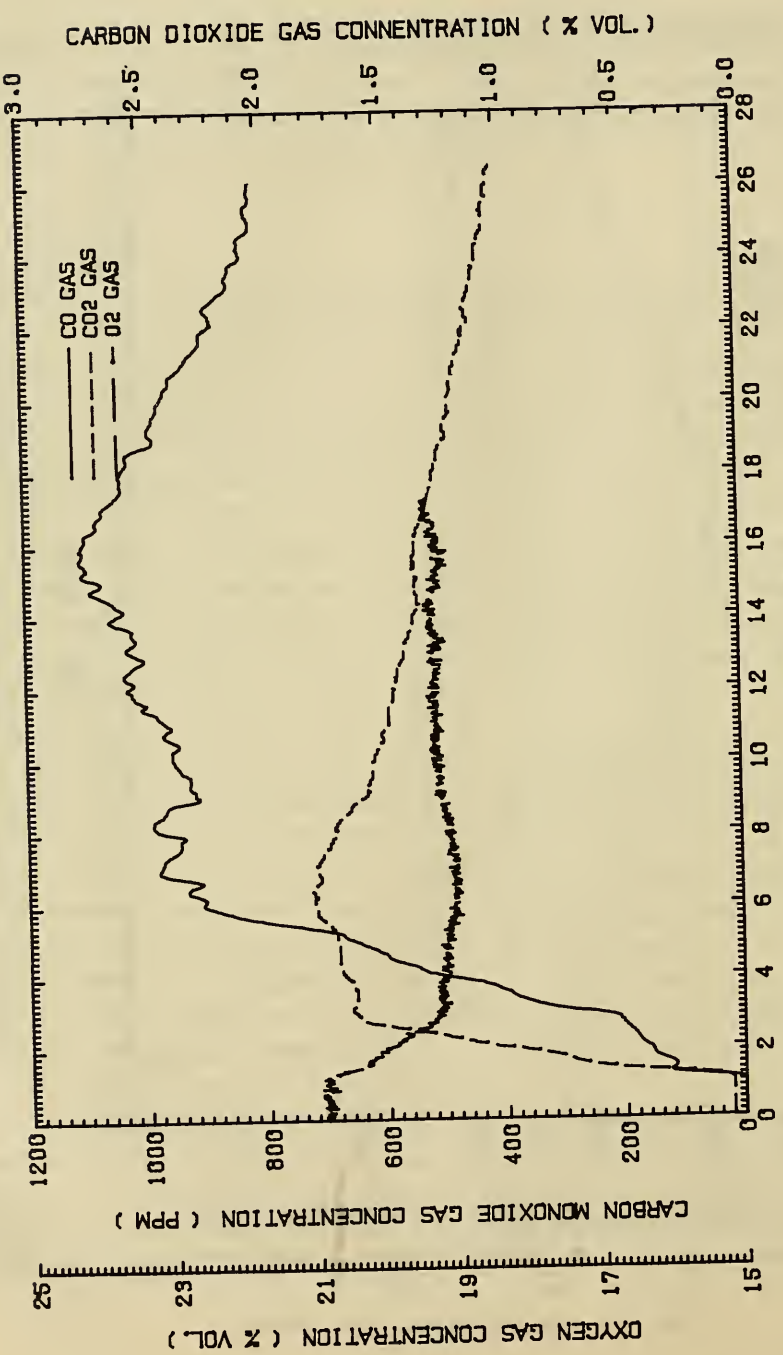

FACTORY MUTUAL RESEARCH CORPORATION
FMRC SERIAL NO. 22574
CARBON DIOXIDE GAS CONNENTRATION (% VOL.)
CO GAS
CO2 GAS
O2 GAS
TIME (MIN.)
CARBON MONOXIDE GAS CONCENTRATION (PPM)
OXYGEN GAS CONCENTRATION (% VOL.)

FIGURE 36 CO, CO_2 AND O_2 CONCENTRATIONS AT EYE LEVEL FOR TEST S1.2

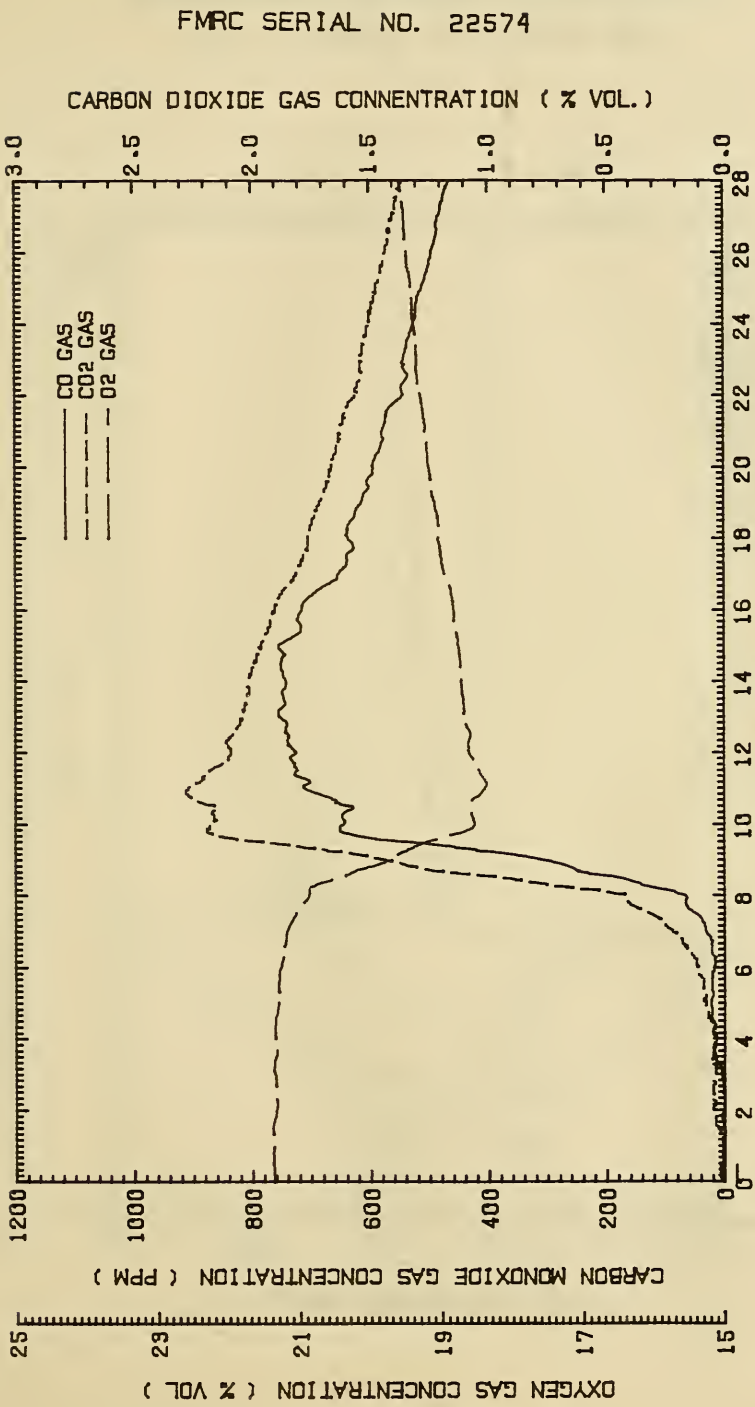

FACTORY MUTUAL RESEARCH CORPORATION
FMRC SERIAL NO. 22574
CARBON DIOXIDE GAS CONNENTRATION (% VOL.)
CO GAS
CO2 GAS
O2 GAS
TIME (MIN.)
CARBON MONOXIDE GAS CONCENTRATION (PPM)
OXYGEN GAS CONCENTRATION (% VOL)

FIGURE 37 CO, CO_2 AND O_2 CONCENTRATIONS AT EYE LEVEL FOR TEST S1.3

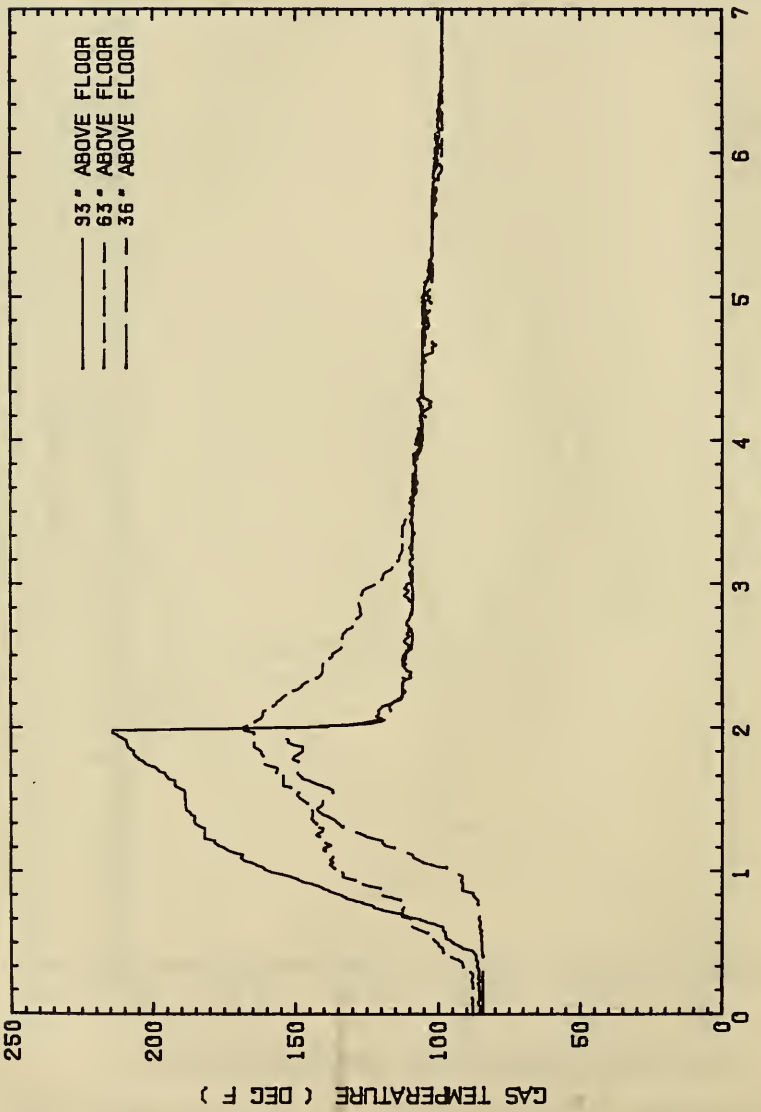


FIGURE 38 GAS TEMPERATURES AT THREE ELEVATIONS, 93, 63 AND 36 in. ABOVE THE FLOOR FOR TEST S1.1

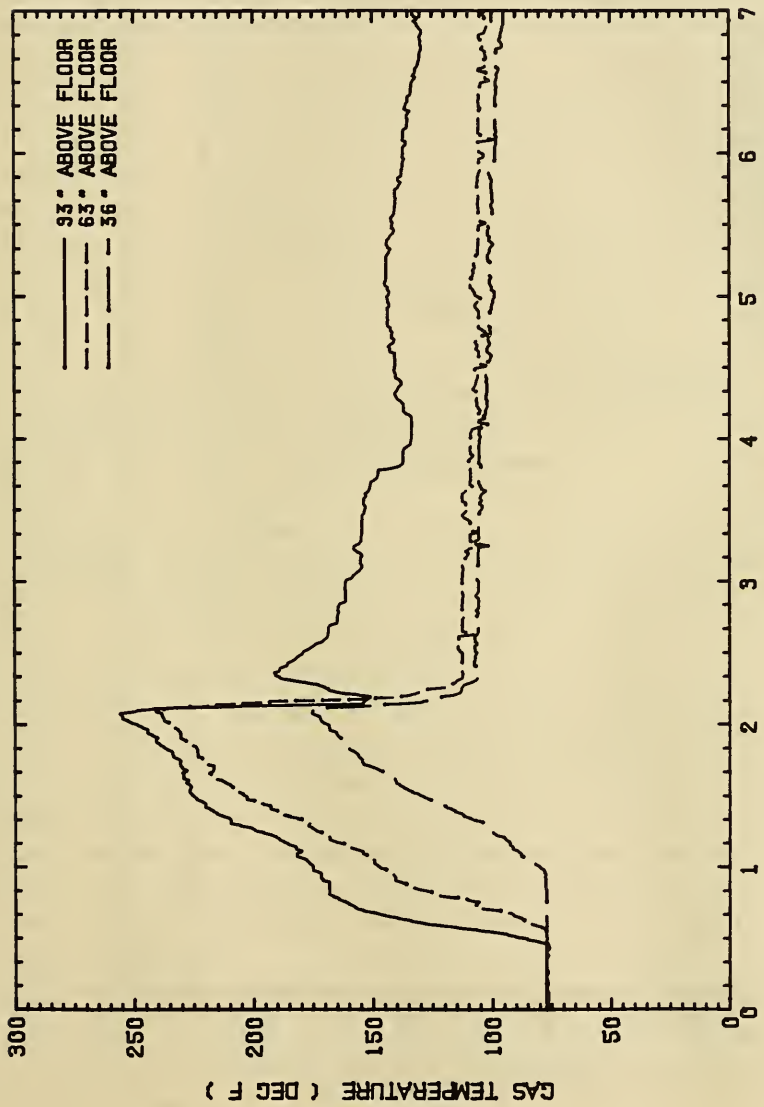


FIGURE 39 GAS TEMPERATURES AT THREE ELEVATIONS, 93, 63 AND 36 in. ABOVE THE FLOOR FOR TEST S1.2

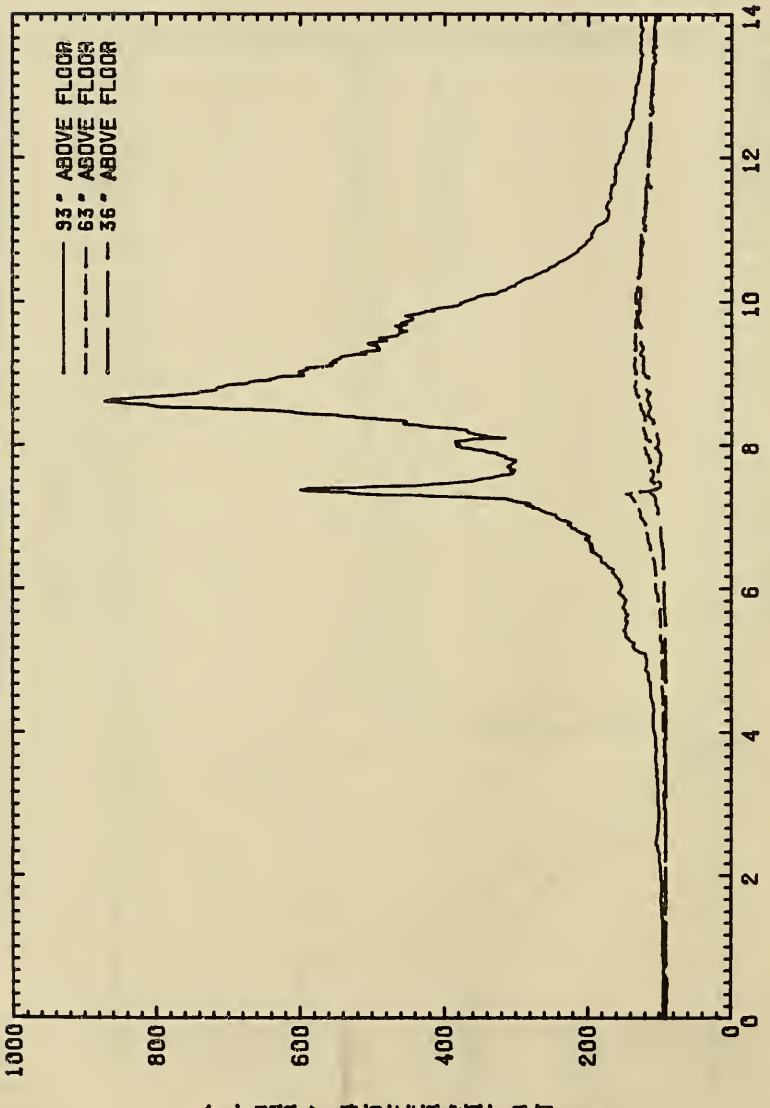


FIGURE 40 GAS TEMPERATURES AT THREE ELEVATIONS, 93, 63 AND 36 in. ABOVE THE FLOOR FOR TEST S1.3

For the living room fire test, the gas temperatures had two maxima. The first maximum occurred at about the time of first sprinkler operation (7 min, 20 sec after ignition) when the side of the chair became involved and fire spread to the curtains behind the chair. Although sprinkler water suppressed the fire for a short time, fire gradually spread to the back side of the chair and developed to a greater intensity (see Figure 40) at which time the second maximum of the gas temperature occurred. (The second sprinkler was activated at 8 min, 12 sec after ignition.) The fire at the back of the chair was totally shielded from the sprinkler spray. Direct extinction by water delivered to the burning surface could not be achieved. The tested spray was not capable of suppressing the fire and cooling the gases sufficiently. The average water application density w_c, over the 25 pans used as an indicator for the amount of sprinkler water delivered over the fire source was only 0.015 gpm/ft^2 (Figure 27). However, enough sprinkler water reached the window and the plywood panel above the chair on the north wall to drip along the panel directly behind the chair and prevent it from igniting. The vertical water distribution w_v over the 1 ft wide x 2.5 ft high area on the wall above the chair shown in Figure 26 is 0.011 gpm/ft^2 (Figure 27).

Ceiling surface temperatures for the three tests are presented in Figure 41. The maximum ceiling surface temperatures over the ignition point for all the three tests were maintained below 300°F. In this test series, combustible walls and ceiling were used but were not involved in the fires.

The gas temperature and velocity histories in the vicinity of the sprinkler for the bedroom and small-bedroom fire tests are shown in Figures 42 and 43 respectively. Gas temperature and velocity histories adjacent to the two sprinklers in the living room fire test are presented in Figures 44 and 45. This information can be used to characterize fire growth rates and to predict the sprinkler response time. Judging from the gas temperature and velocity measurements at the second sprinkler in the living room fire test, it is expected that sprinklers with the same sensitivity in the hallway and kitchen would have been actuated.

Although "smokiness" in the sense of visibility is not judged to be a critical factor in human survivability during a sprinklered fire, the optical density is still of considerable interest. Figure 46 presents optical densities at eye level for the three tests.

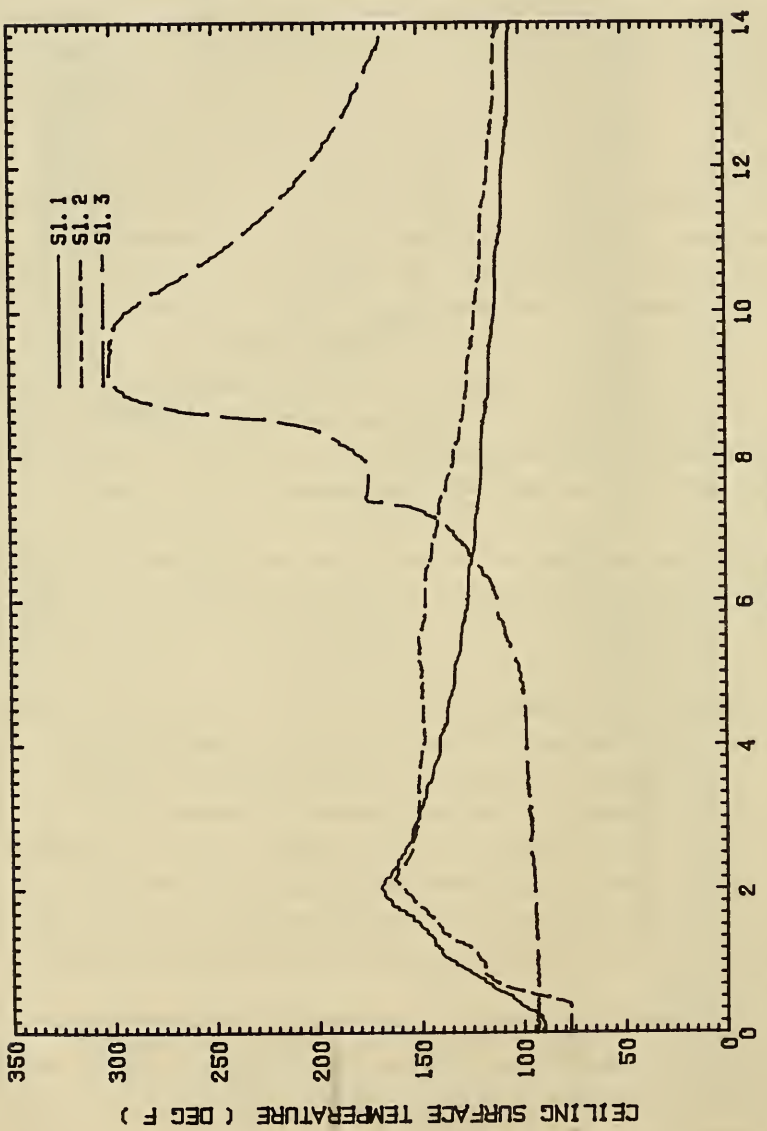


FIGURE 41 CEILING SURFACE TEMPERATURES ABOVE IGNITION FOR TESTS S1.1, S1.2, AND S1.3

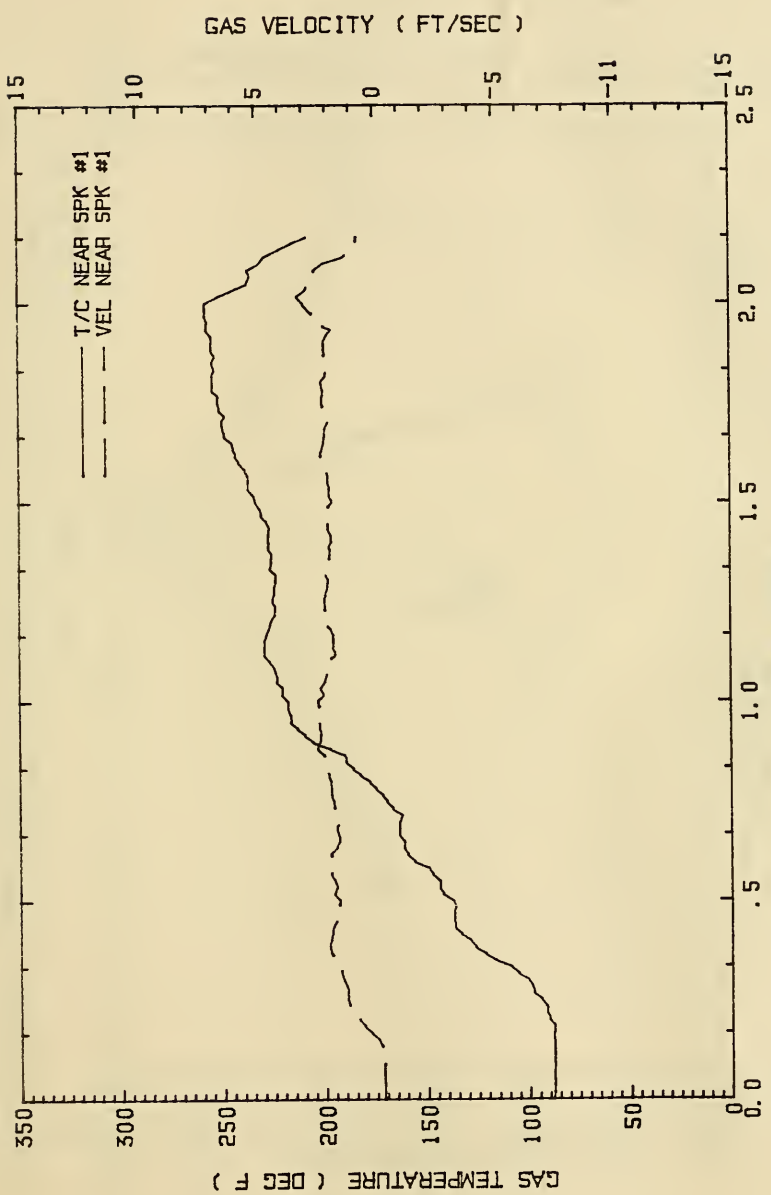


FIGURE 42 GAS TEMPERATURE AND VELOCITY IN VICINITY OF THE SPRINKLER
TEST S1.1

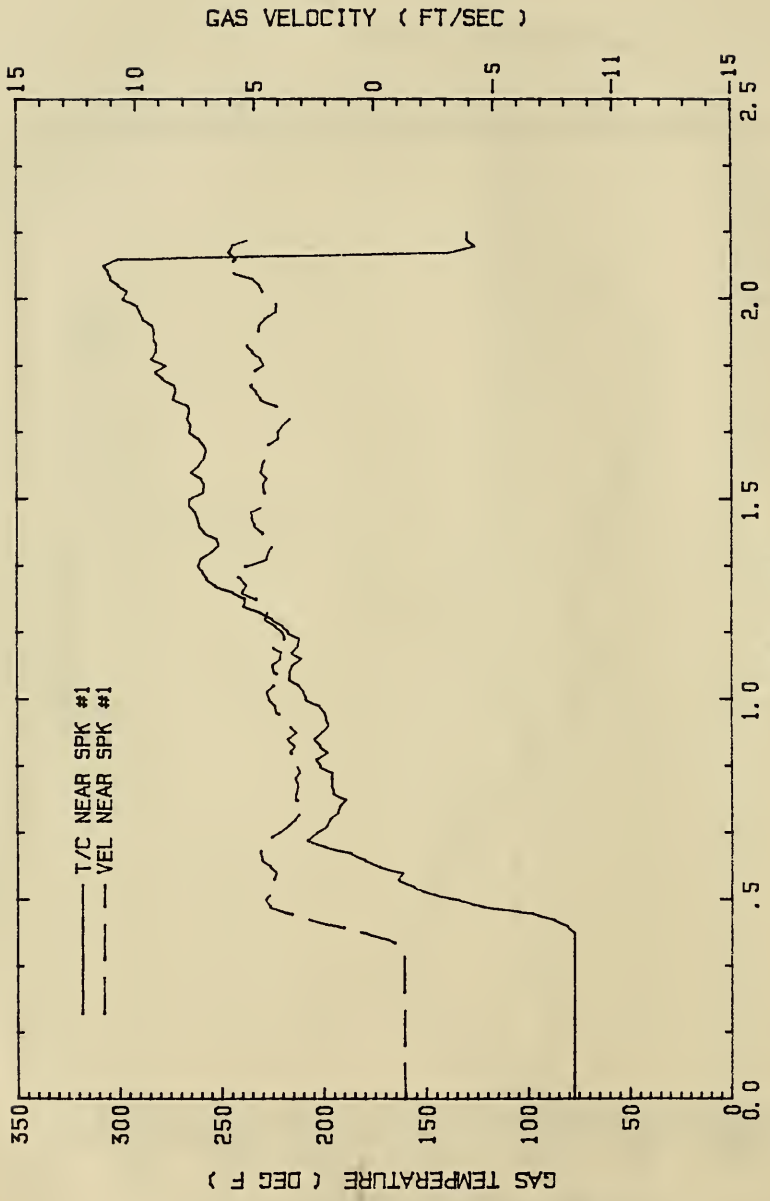


FIGURE 43 GAS TEMPERATURE AND VELOCITY IN THE VICINITY OF THE SPRINKLER
TEST S1.2

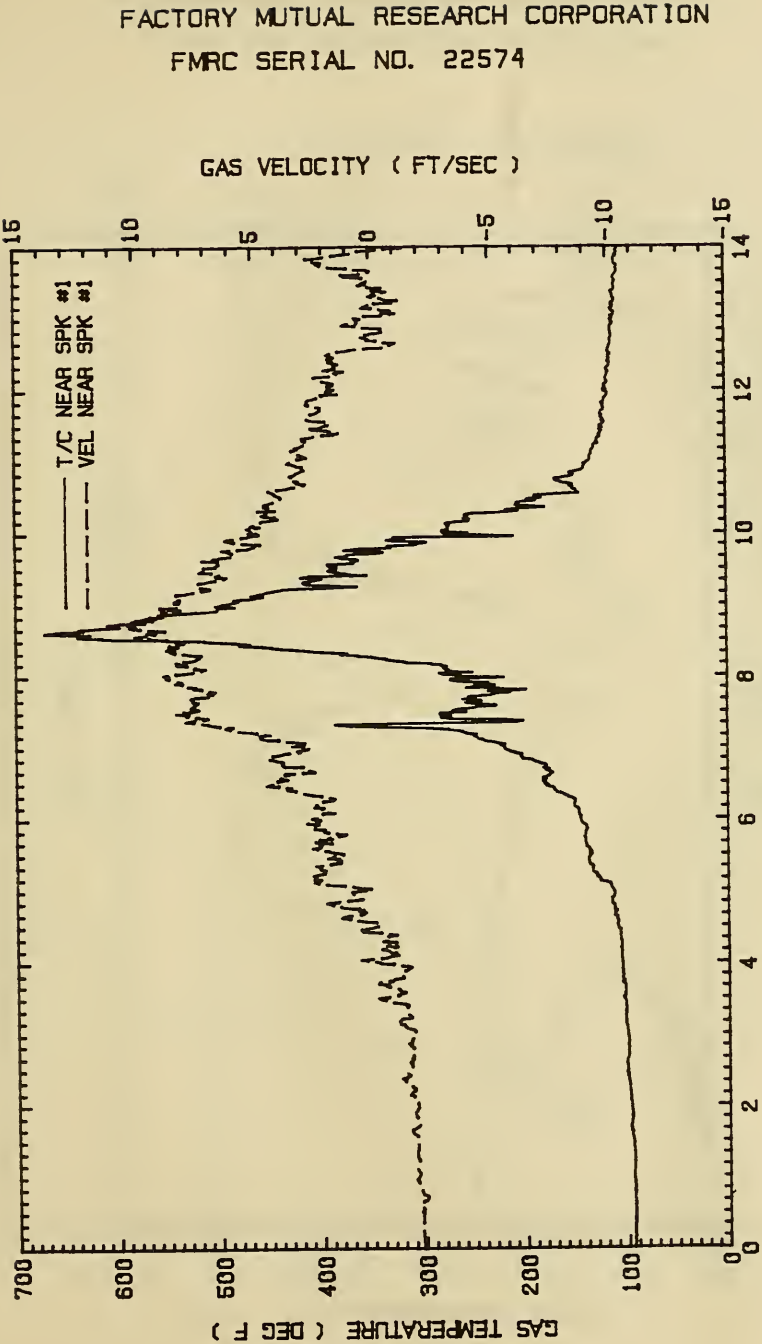

FACTORY MUTUAL RESEARCH CORPORATION
FMRC SERIAL NO. 22574
GAS VELOCITY (FT/SEC)
T/C NEAR SPK #1
VEL NEAR SPK #1
GAS TEMPERATURE (DEG F)
TIME (MIN.)

FIGURE 44 GAS TEMPERATURE AND VELOCITY ADJACENT TO SPRINKLER NO. 1 - TEST S1.3

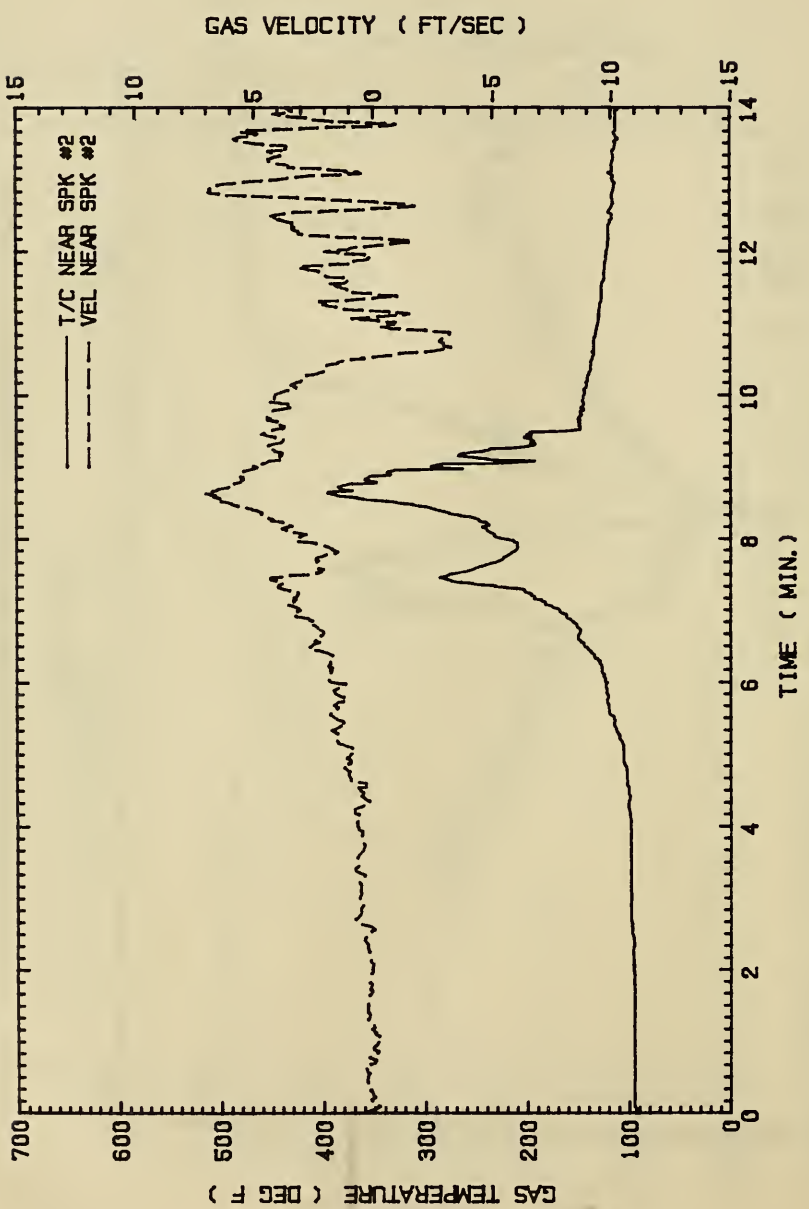

FACTORY MUTUAL RESEARCH CORPORATION
FMRC SERIAL NO. 22574
GAS VELOCITY (FT/SEC)
T/C NEAR SPK #2
VEL NEAR SPK #2
GAS TEMPERATURE (DEG F)
TIME (MIN.)

FIGURE 45 GAS TEMPERATURE AND VELOCITY ADJACENT TO SPRINKLER NO. 2 - TEST S1.3

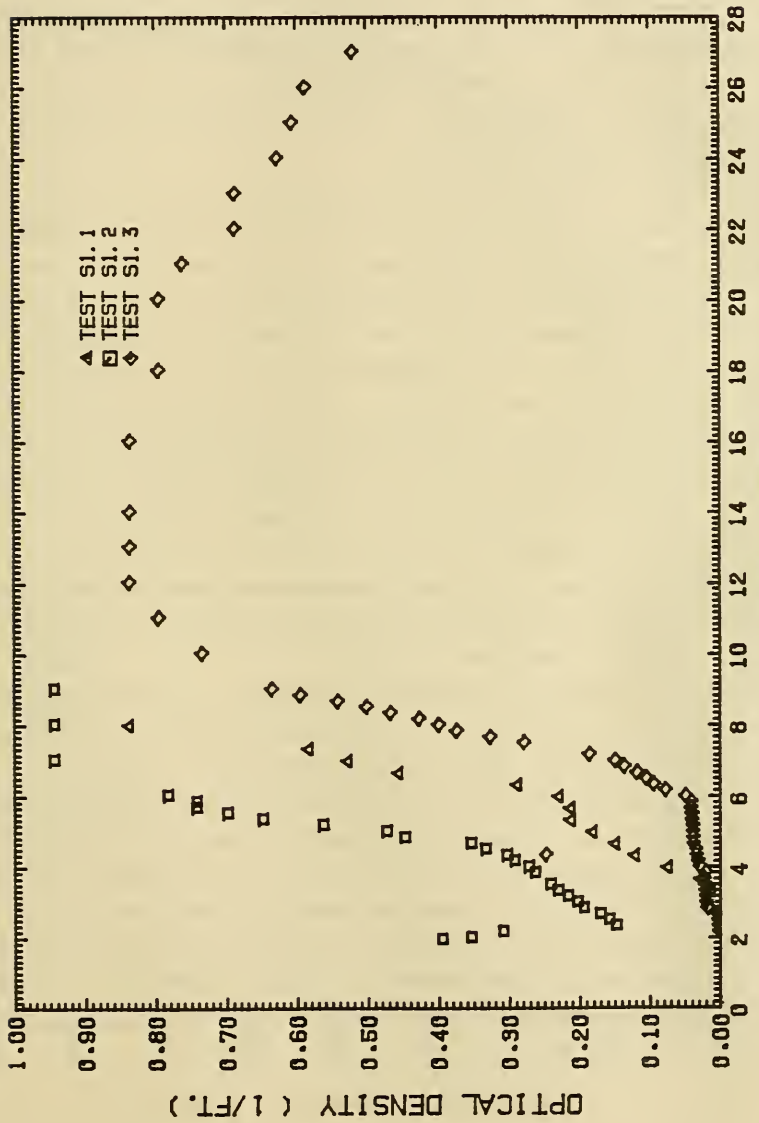


FIGURE 46 OPTICAL DENSITY AT EYE LEVEL - TESTS S1.1,S1.2 AND S1.3

6.2.2 Test Series 2

Sprinkler variables of the three ventilated living room fire tests with noncombustible walls and ceiling are listed in Table II. Only commercial, 5/16-in. orifice sprinklers were used. In Tests S2.1 and S2.2 the sprinkler links had a time constant of 73.9 sec and were rated at 165°F. In Test S2.3, the sprinklers were activated by simulated links of 16.9 sec time constant rated at 140°F. The water discharge rate from each sprinkler was 6 gpm in Tests S2.1 and S2.3 and 9 gpm in Test S2.2.

In order to compare the fire growth of the nonventilated and ventilated living room fires, gas temperatures in the vicinity of the sprinkler closest to the fire source (Sprinkler No. 1) for Tests S1.3, S2.1 and S2.2 are plotted in Figure 47. The reference point of the time abscissa was selected at time, t_r, when the sprinkler link temperature increased 71°F from its initial temperature. Time, t_r, was computed with the aid of temperature and velocity measurements adjacent to Sprinkler No. 1. The computation scheme is detailed in Appendix B. In Test S1.3, the difference between the rated fusing temperature of the link and the initial link temperature was also 71°F; therefore, time, t_r, should be very close to the sprinkler activation time. The computed value t_r for Test S1.3 happened to be the same as the actual time of sprinkler activation. Figure 47 shows that, at time, t_r, the gas temperature adjacent to Sprinkler No. 1 in Test S1.3 only increased 292°F, whereas the increases of gas temperatures in Tests S2.1 and S2.2 were over 359°F.

Figure 48 shows gas velocities adjacent to Sprinkler No. 1 for Tests S1.3, S2.1 and S2.2. At time, t_r, the gas velocity in Test S1.3 was only 6.8 ft/sec; however, in Tests S2.1 and S2.2, gas velocities were over 11 ft/sec.

In Test S1.3 at time, t_r, the side of the chair was not completely involved in the fire and the curtains behind the chair had just ignited. However, in Tests S2.1 and S2.2 at time, t_r, the side of the chair was completely engulfed in flames and the full length of the curtains behind the chair was burning.

These results indicate that, in order for a sprinkler link with a certain sensitivity to achieve the same temperature rise in both a ventilated fire and a nonventilated fire, the ventilated fire would have to grow to a higher intensity than the nonventilated fire.

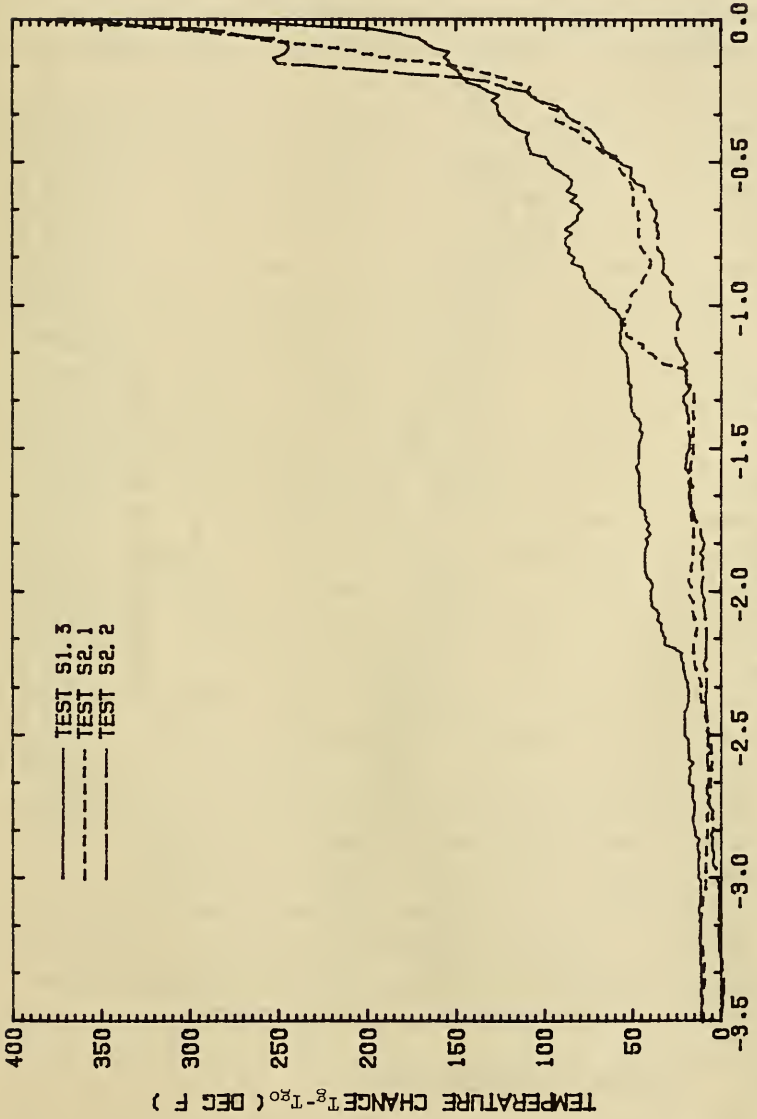


FIGURE 47 COMPARISON OF FIRE GROWTH BETWEEN NONVENTILATED FIRE (TEST S1.3) AND VENTILATED FIRE (TESTS S2.1 AND S2.2) IN TERMS OF GAS TEMPERATURE ADJACENT TO SPRINKLER NO. 1 (t_r is the time at which the sprinkler link temperature increased 71°F from its initial temperature.)

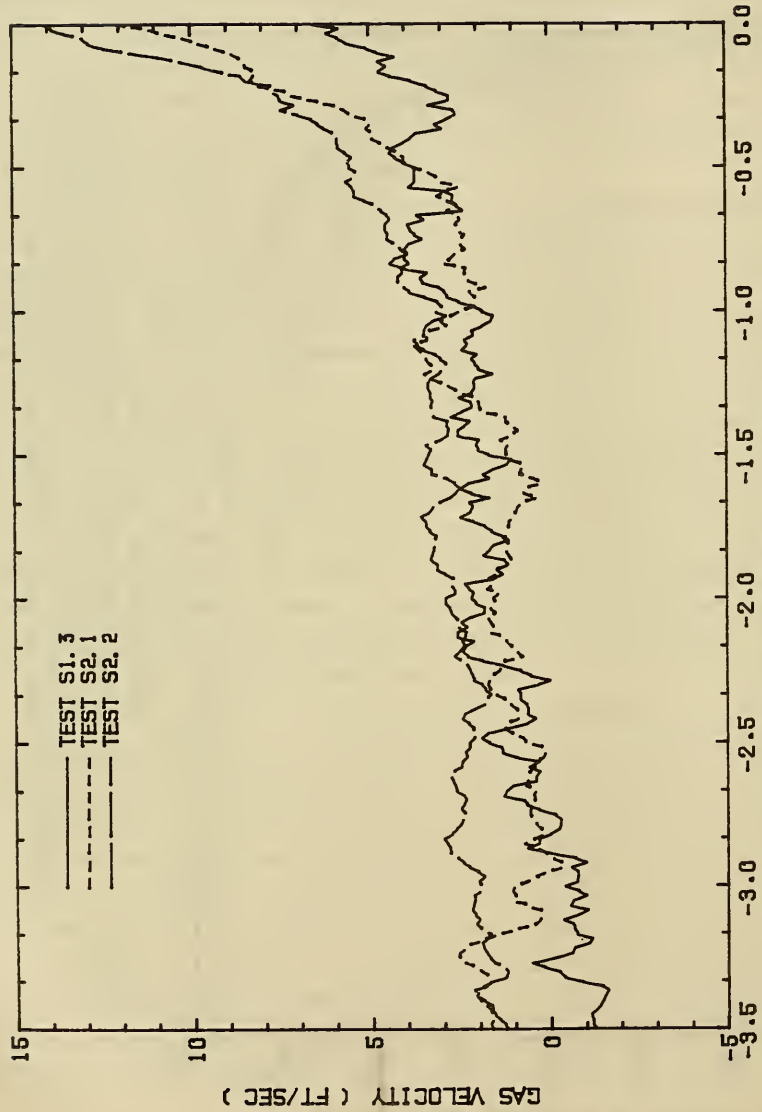


FIGURE 48 COMPARISON OF FIRE GROWTH BETWEEN NONVENTILATED FIRE (TEST S1.3) AND VENTILATED FIRE (TESTS S2.1 AND S2.2) IN TERMS OF GAS VELOCITY ADJACENT TO SPRINKLER NO. 1 (t_r is the time at which the sprinkler link temperature increased 71°F from its initial temperature.)

In Tests S2.1 and S2.2, commercially available sprinkler links with the same sensitivity and temperature rating were employed; however, the sprinkler discharge rates were different, 6 gpm for Test S2.1 and 9 gpm for Test S2.2. For Tests S2.1 and S2.2, the gas temperature adjacent to Sprinkler No. 1 increased after sprinkler activation as shown in Figure 49. The reference point of the time abscissa is the time of sprinkler activation. In Test S2.1, the maximum gas temperature was 1577°F at 26 sec after sprinkler activation, whereas in Test S2.2 the maximum gas temperature was 1090°F at 75 sec after sprinkler activation. The CO concentration and gas temperature at eye level and the ceiling surface temperature over the ignition point are shown in Figures 50, 51 and 52 respectively. In Test S2.1, the maximum CO concentration was over 10,000 ppm, beyond the range of the CO analyzer. Table VIII lists maximum values of CO, CO_2 concentrations, O_2 deficiency and gas temperature at eye level; and the ceiling surface temperature. The maximum values for Test S2.2 are considerably lower than those for Test S2.1; however, all these values have exceeded the critical values adopted for evaluation of sprinkler performance.

The average water application density, w_c, over the 25 pans represented by the shaded area in the floor water distribution plan in Figures 27 to 34 is used as an indicator for the amount of sprinkler water reaching over the fire source in the corner. For Tests S2.1 and S2.2, the values, w_c, were 0.015 and 0.023 gpm/ft^2 respectively (Figures 27 and 28). The fire test results indicate that a sprinkler activated by a link of 73.9 sec time constant rated at 165°F, delivering an average density of 0.023 gpm/ft^2 over the 5 ft x 5 ft shaded area was not capable of providing adequate life safety and property protection in the fire test.

In Tests S2.1 and S2.2, at the time of the first sprinkler operation, the fire was already in the very rapidly accelerating stage. The fire had spread to the full length of the curtains. The side of the chair was burning intensely and flames were sweeping across the ceiling. In Test S2.1, fire jumped to the side of the sofa 1 sec before sprinkler activation. In order to suppress a fire already developed to such an extent, significantly higher sprinkler discharge rates would be required than employed in these tests to ensure sufficient application density over the fire source. Using a more sensitive sprinkler link, it is expected that the sprinkler discharge rate required to control the fire would be smaller than that with the commercially available link.

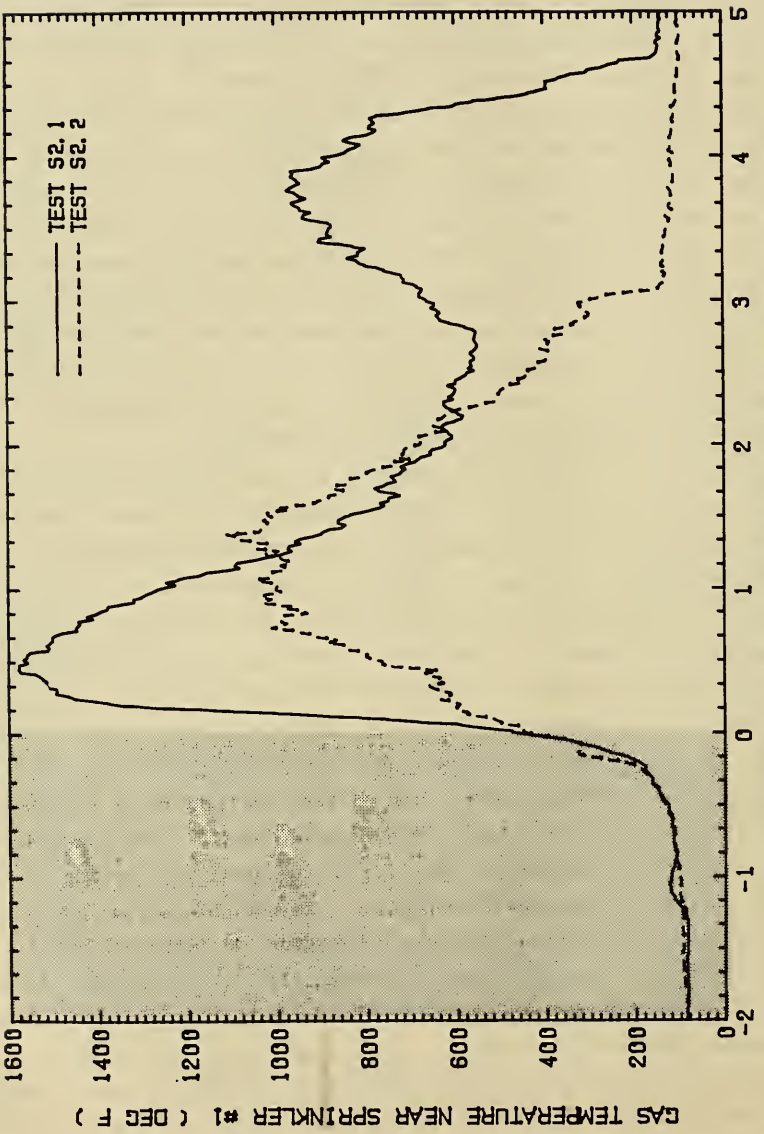


FIGURE 49 GAS TEMPERATURE ADJACENT TO SPRINKLER NO. 1 - TESTS S2.1 AND S2.2

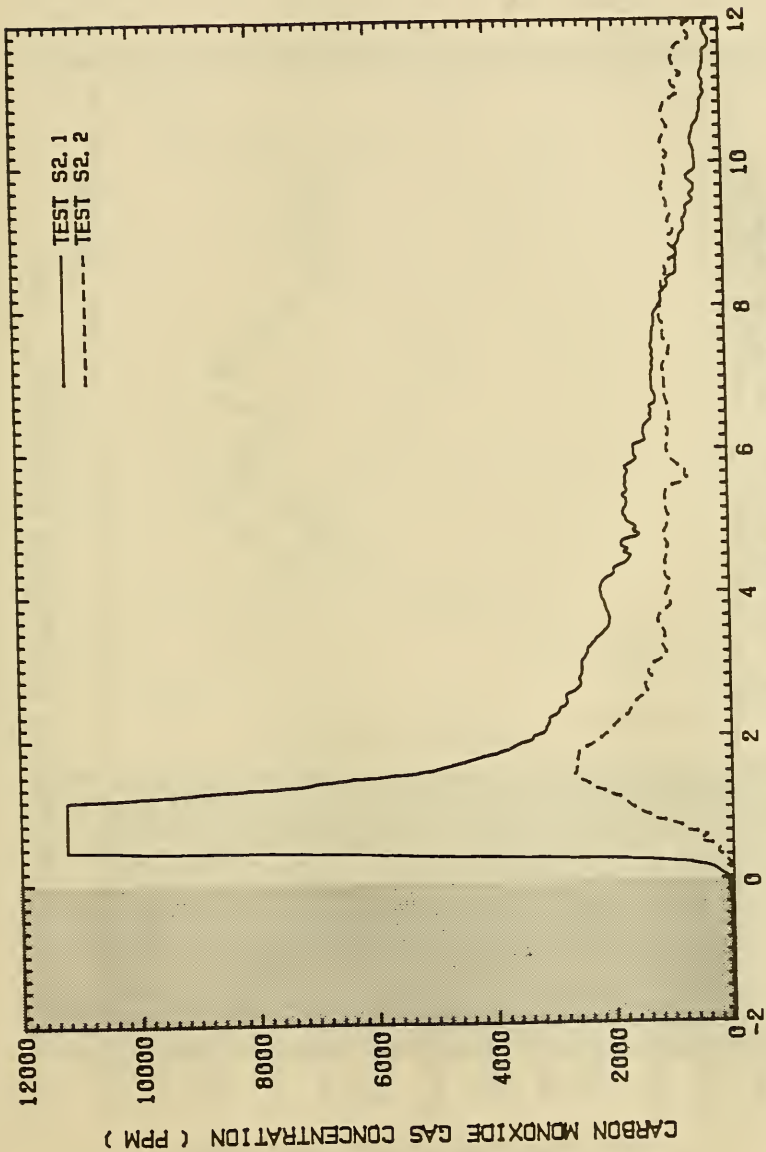


FIGURE 50 CO CONCENTRATION AT EYE LEVEL - TESTS S2.1 AND S2.2

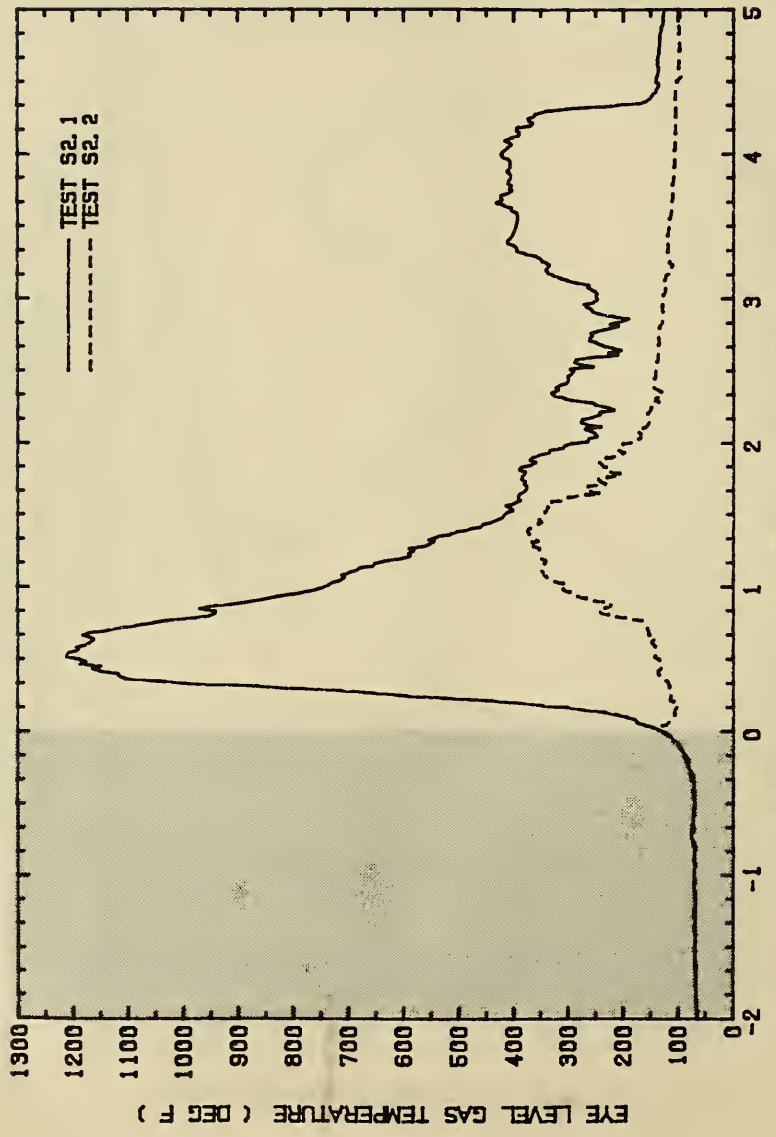


FIGURE 51 GAS TEMPERATURE AT EYE LEVEL - TESTS S2.1 AND S2.2

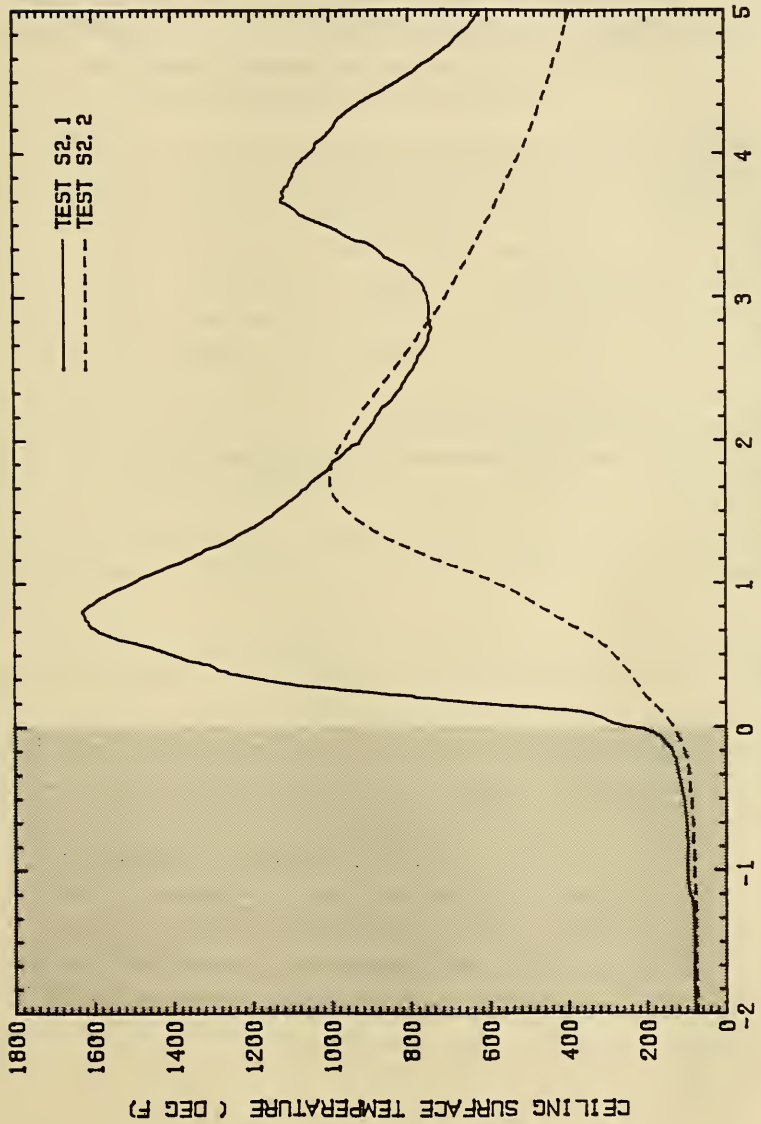


FIGURE 52 CEILING SURFACE TEMPERATURE OVER IGNITION POINT - TESTS S2.1 AND S2.2

TABLE VIII

MAXIMUM VALUES OF CO, CO_2 GAS CONCENTRATIONS, AND GAS TEMPERATURE AT EYE LEVEL, AND CEILING SURFACE TEMPERATURE ABOVE IGNITION POINT FOR TEST SERIES 2

Test	S2.1	S2.2	S2.3
CO (ppm)	over 10,000	2,640	450
CO_2 (%)	over 10.00	5.4	1.2
O_2 deficiency (%)	10.8	6.4	1.6
T_e (°F)	1,212	354	122
T_c (°F)	1,629	1,001	295

Note: T_e: Gas temperature at eye level
T_c: Ceiling surface temperature above ignition point

In Test S2.3, simulated links with much higher sensitivity were used for sprinkler activations. Links were selected to have a sensitivity such that, as the link reached the rated temperature, 140°F, the curtains behind the chair would have just ignited and the major burning item would be still limited to the chair. The determination of the time constant of such a link was based on the histories of gas temperature and velocity adjacent to Sprinkler No. 1 in Tests S2.1 and S2.2 (see Appendix B).

The effect of sprinkler response time is investigated by comparing the results of Tests S2.1 and S2.3 which had the same water discharge rate but different link sensitivities. CO gas concentrations and gas temperatures at eye level, ceiling surface temperatures, and gas temperatures and velocities adjacent to Sprinkler No. 1 are plotted in Figures 53, 54, 55, 56 and 57 respectively. For Test S2.3 the reference point of the time abscissa is the activation time of Sprinkler No. 1 (at which time the simulated link temperature increased 71°F from its initial temperature), whereas for Test S2.1, the reference point of the time abscissa is the time, t_d, at which the temperature of a 16.9 sec time-constant simulated link would increase by 71°F. Figures 53, 54 and 55 demonstrate that the commercial 5/16-in. orifice sprinkler activated by a simulated link with a 16.9-sec time constant, rated at 140°F, discharging 6 gpm is capable of providing adequate life-safety and property protection in such a fast-growing fire.

In Test S2.3, at the time of sprinkler activation, the gas temperature adjacent to Sprinkler No. 1 was only 202°F and the gas velocity was 6.5 ft/sec. Fire then gradually spread to the backside of the chair and was completely shielded from the sprinkler spray. As in the nonventilated living room fire test, the sprinkler spray tested was not capable of suppressing the fire and cooling the gases sufficiently, and the gas temperature reached a maximum value of 637°F, 129 sec after sprinkler activation.

The thermal responses of the three simulated links (16.7 sec time constant at 7.4 ft/sec) located at Sprinklers Nos. 1 and 2 and in the hallway are shown in Figure 58. The maximum temperature of the link in the hallway reached 280°F. As sprinkler water impinged on the link adjacent to the sprinkler, the temperature of the link dropped sharply. Since there was no sprinkler installed in the hallway, the hallway link did not experience such a sharp drop,

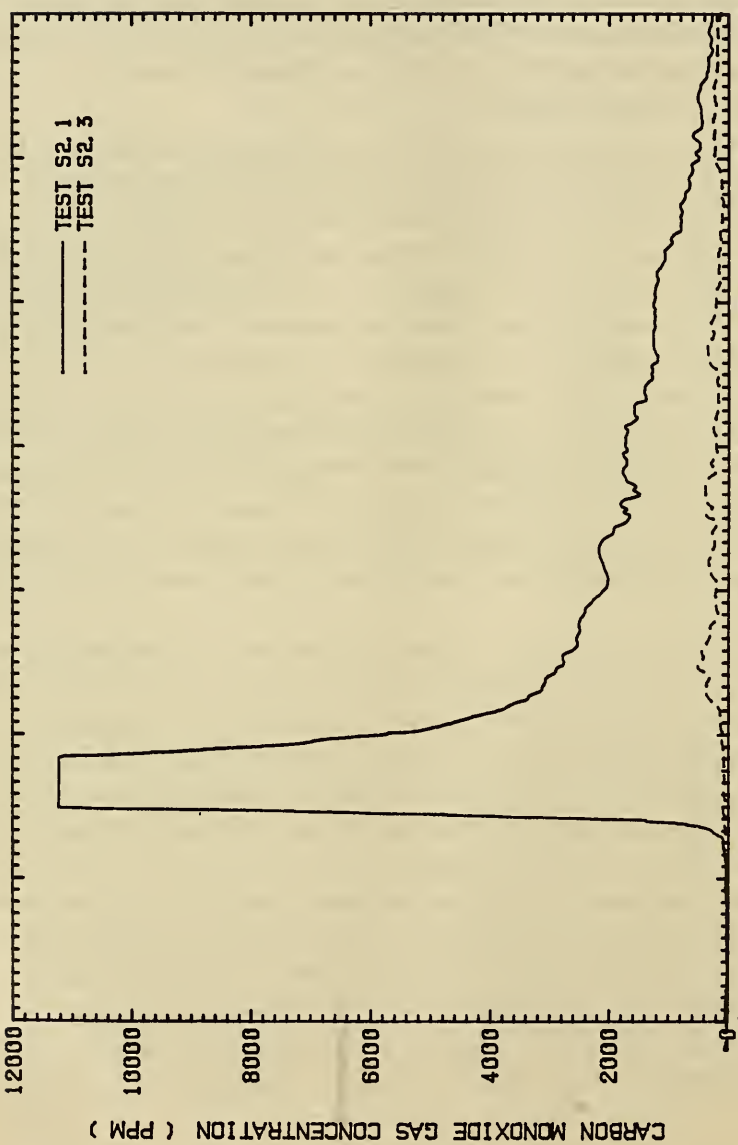


FIGURE 53 CARBON MONOXIDE GAS CONCENTRATION AT EYE LEVEL-TESTS S2.1 AND S2.3
(Note: t_d= time at which the temperature of a 16.9 second time constant link would increase,or increased,by 71°F)

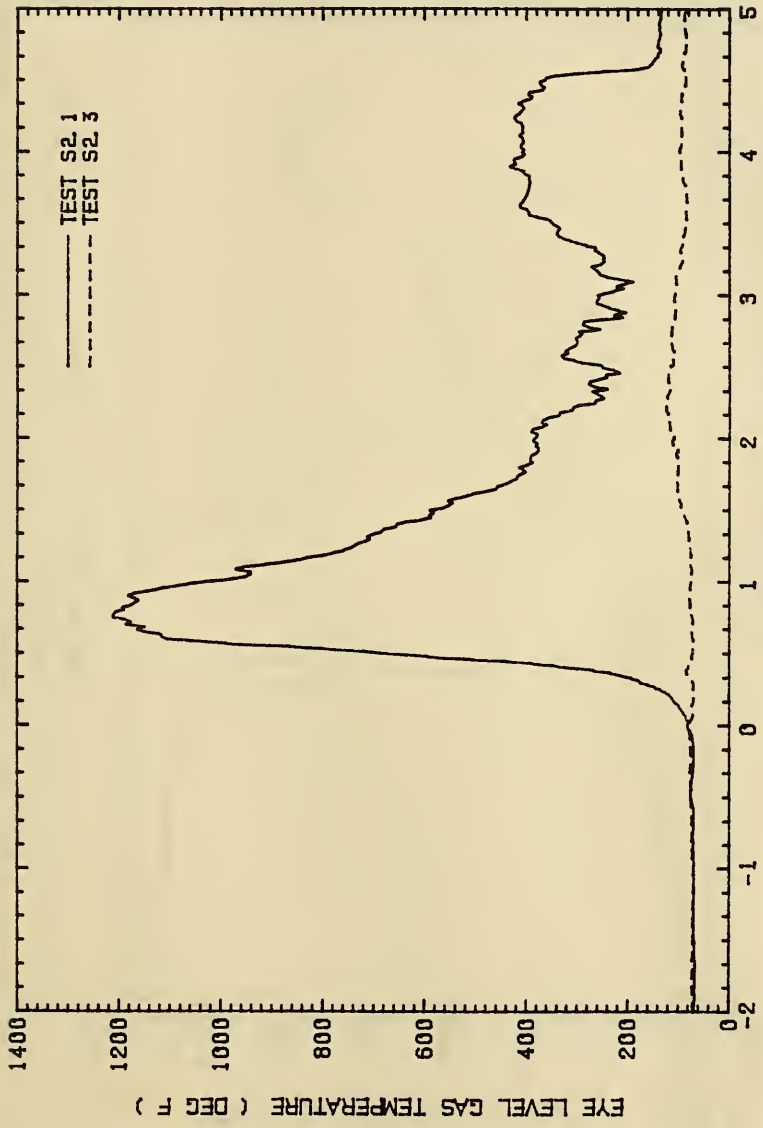


FIGURE 54 GAS TEMPERATURE AT EYE LEVEL - TESTS S2.1 AND S2.3
(Note: t_d=time at which the temperature of a 16.9 second time constant link would increase,or increased,by 71^{o}_{F})

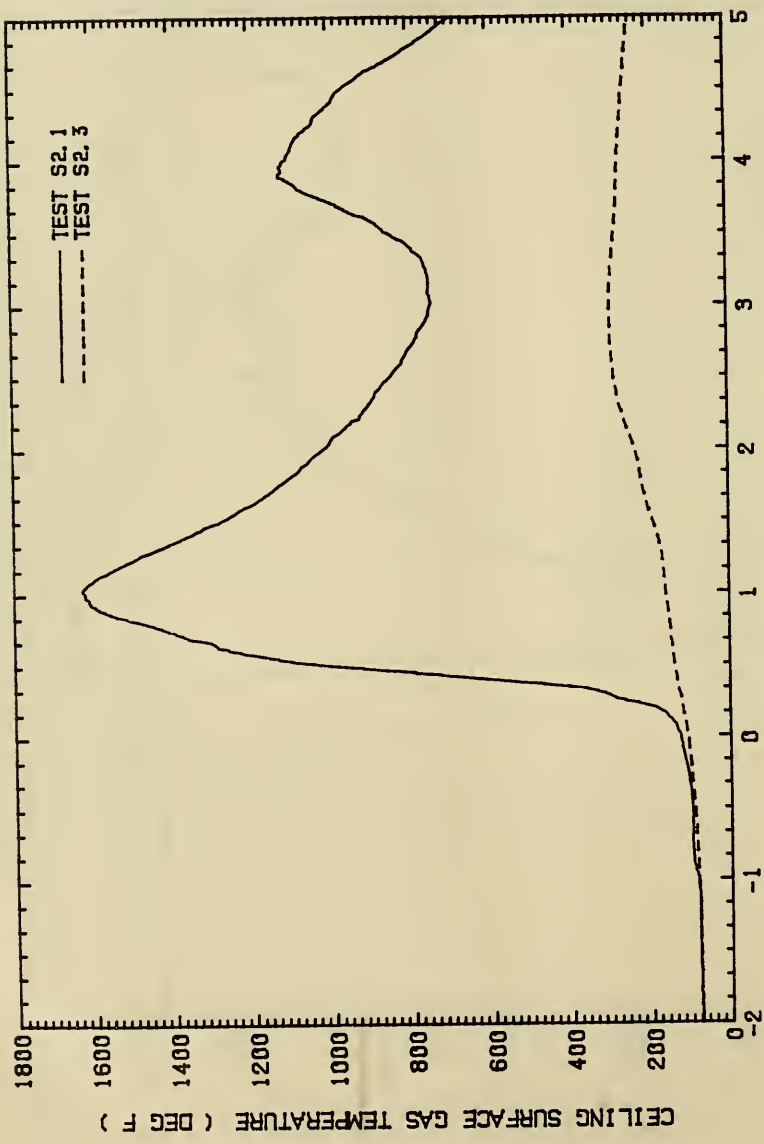


FIGURE 55 CEILING SURFACE TEMPERATURE - TESTS S2.1 AND S2.3
(Note: t_d= time at which the temperature of a 16.9 second time constant link would increase,or increased,by 71°F)

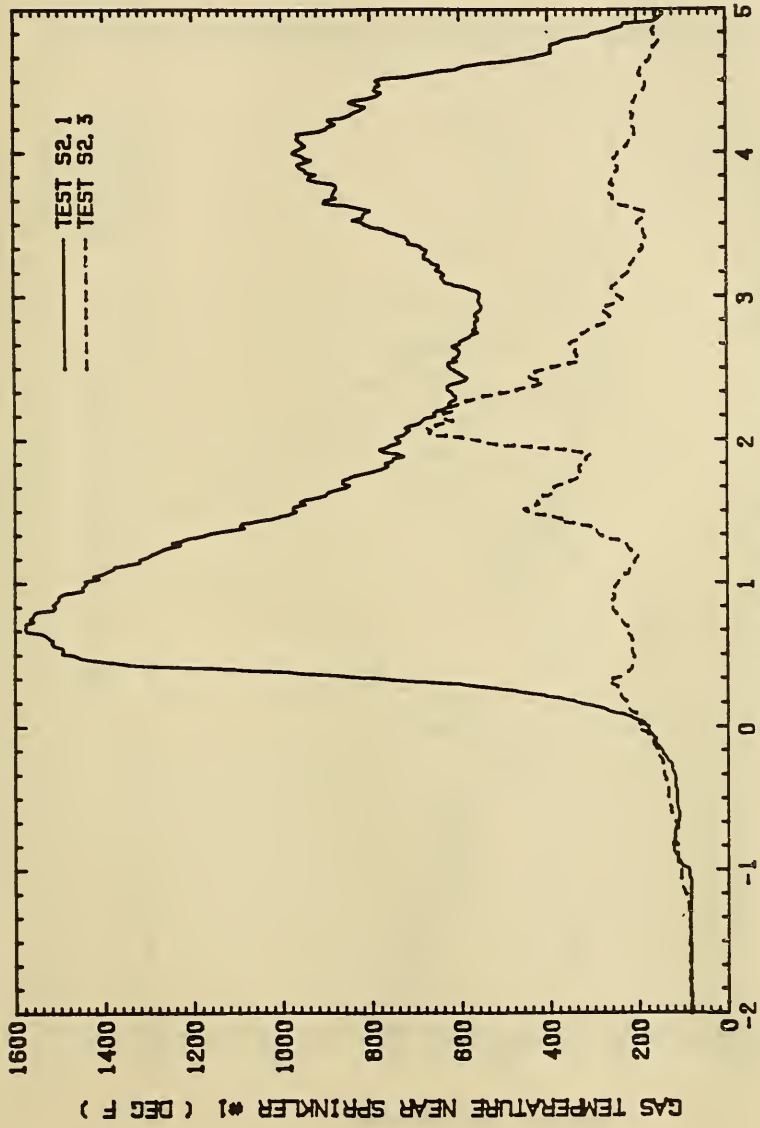


FIGURE 56 GAS TEMPERATURE ADJACENT TO SPRINKLER NO. 1 - TESTS S2.1 AND S2.3
(Note: t_d = time at which temperature of 16.9-sec time constant link would increase, or increased, by 71°F)

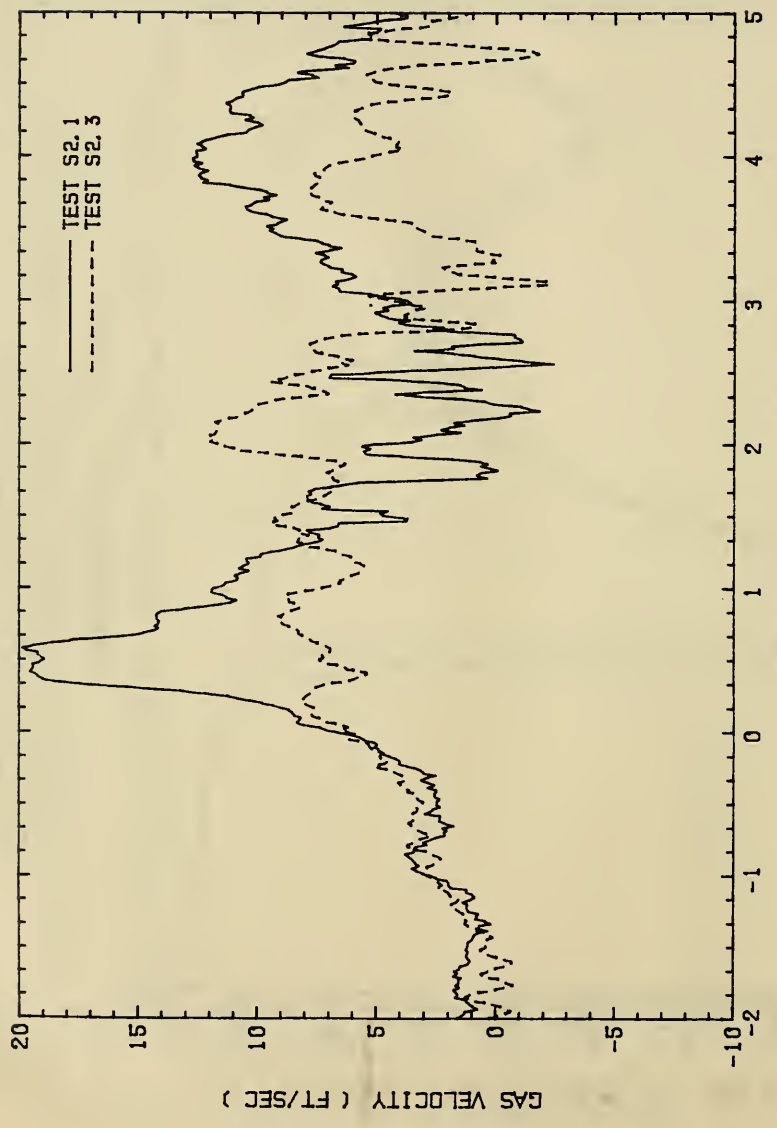


FIGURE 57 GAS VELOCITY ADJACENT TO SPRINKLER NO.1 - TEST S2.1 AND S2.3
(Note: t_d = time at which the temperature of a 16.9 second time constant link would increase, or increased, by 71°F)

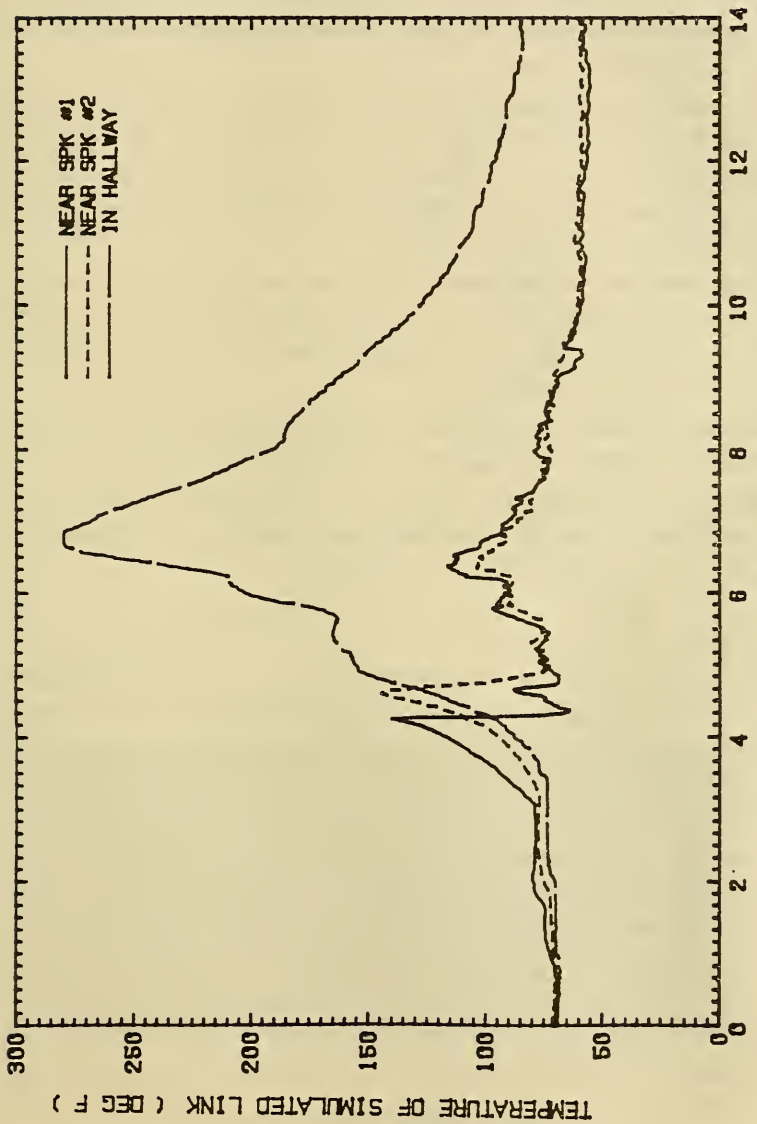


FIGURE 58 TEMPERATURE OF THREE SIMULATED LINKS LOCATED AT SPRINKLERS NO. 1 AND 2 AND IN HALLWAY - TEST S2.3

although a sprinkler with the same sensitivity rated at 145°F adjacent to the link would have operated. It is expected that a sprinkler with the same link (rated at 140°F) in the kitchen would also have operated. In order to prevent excessive sprinkler openings, a higher water discharge rate is required so that an adequate amount of water will be delivered to the corner of the room to suppress the fire and cool the gases.

The gas temperatures measured 5 13/16 in. beneath the top edge of the northwest window are plotted in Figure 59 for the three tests in Test Series 2. The maximum values for Tests S2.1, S2.2 and S2.3 are 1477°F, 415°F and 250°F respectively. For Test S2.1 the potential of fire spread to the exterior combustible structure was very high.

Figure 60 shows gas temperatures 10 in. from the top of the entry doorway. The maximum values for Tests S2.1, S2.2 and S2.3 are 509°F, 368°F and 249°F respectively. The likelihood of fire spread to the rest of the building is considered to be small in all these cases.

The maximum values of gas temperature in the entry door at the 55 in. level were 541°, 282°, and 125°F for Tests S2.1, S2.2 and S2.3, respectively. Therefore, the egress route through the entry door in Tests S2.1 and S2.2 was not maintained sufficiently safe by sprinklers for occupants to be rescued or to escape.

6.2.3 Test Series 3

Test Series 3 consisted of seven ventilated living room fire tests with combustible walls and ceiling. The initial fire development of Test Series 3 was similar to that of Test Series 2. However, the presence of the combustible walls and ceiling added a greater fire challenge to the sprinklers. With the commercially available link, at the time of sprinkler activation the fire started to spread to the plywood panels and flames were sweeping across the ceiling. Therefore, it is even more critical in such fires to have a more sensitive link to activate the sprinkler when the major burning activity is still limited to the chair than in fires with noncombustible walls and ceiling. Furthermore, a sufficient amount of sprinkler water over the fire source is required to suppress the fire to prevent the ceiling panels from igniting, and adequate wetting of the combustible walls is essential to stop fire spread from the chair to the walls.

FIGURE 59 GAS TEMPERATURE AT 5 13/16 IN. BENEATH THE TOP EDGE OF THE NORTHWEST WINDOW TESTS S2.1, S2.2, AND S2.3

FIGURE 60 GAS TEMPERATURE AT 10 IN. FROM TOP OF ENTRY DOORWAY - TESTS S2.1, S2.2, S2.3

In this test series, four different types of sprinklers were used: the experimental 0.275-in. orifice sprinkler; the experimental 0.329-in. orifice sprinkler; the manufacturer's prototype 1; and manufacturer's prototype 2. The sprinkler variables tested have been presented in Table III. The effects of link sensitivity, temperature difference between the rated link temperature and the initial link temperature, and sprinkler water distribution on sprinkler performance were investigated.

In Tests S3.1 and S3.2, experimental 5/16-in. orifice sprinklers were used, each discharging 9 gpm. In Test S3.1 commercially available sprinkler links of 73.9 sec time constant rated at 165°F were employed for sprinkler activations, whereas in Test S3.2, simulated links of 16.9 sec time constant rated at 143°F were employed.

At the time of first sprinkler activation in Test S3.1, the full length of the curtains behind the chair was burning, the plywood panel adjacent to the curtains was already ignited, the side of both the chair and the sofa were engulfed in flames and billows of flames were surging across the ceiling. The water spray of the experimental 0.275-in. sprinkler at 9 gpm only reached to a height of 5 ft on the wall behind the chair (Figure 29) and had little or no effect on the fire on the plywood panels above the spray pattern. Only after the plywood panels and ceiling tiles in the northeast corner of the room were consumed did the fire begin to subside.

In Test S3.2, at the time of first sprinkler activation, the fire was still limited to the left side of the chair and the curtains behind the chair. Although the average application density, w_c, delivered by the experimental 0.275-in. sprinkler at 9 gpm over the 5-ft x 5-ft shaded area of the floor water distribution plan shown in Figure 29 is 0.028 gpm/ft^2, considerably higher than that of the commercial 5/16-in. sprinkler at 6 gpm in Test S2.3 (w_c= 0.015 gpm/ft^2), nevertheless the amount of water delivered over the fire source was still not enough to suppress the ventilated fire from igniting the ceiling tile and plywood panel above the fire source. Approximately 1 min after sprinkler operation, the ceiling tile above the chair and the panel above the northeast window were ignited. (In Test 1.3, although the value of w_c delivered by the commercial sprinkler link was 0.015 gpm/ft^2, the combustible ceiling tile and panel above the northeast window did not ignite. This was probably attributable

partly to the lower heat release rate and ceiling flow velocity in the non-ventilated fire.) Furthermore, the application density, w_v, over the 1-ft wide x 2.5-ft high area on the wall above the chair (Figure 29) was only 0.006 gpm/ft^2 in this test. Half a minute later, the fire on the backside of the chair grew to a higher intensity and the panel behind the chair was ignited. In addition, the sprinkler spray only reached 30 in. above the floor in the corner of the room (Figure 29); there was very little prewetting of the plywood panel adjacent to the side of the chair; and consequently, the fire spread to the panel on the east wall.

Gas temperatures adjacent to Sprinkler No. 1 of Tests S3.1 and S3.2 are presented in Figure 61. For Test S3.1, the reference point of the time abscissa is the time, t_d, at which the temperature of a 16.9 sec time constant link would increase by 86°F, whereas for Test S3.2, the reference point is the activation time of Sprinkler No. 1 (at which time the link temperature increased 86°F from its initial temperature). At the time of sprinkler activation, the gas temperatures were 540°F for Test S3.1 and 232°F for Test S3.2. In Test S3.2, fire was controlled by the sprinkler for approximately a minute and the gas temperature was maintained around 170°F; the fire spread along the panel and the gas temperature reached a maximum value of 1100°F. In Test S3.1, the gas temperature continued to increase to a maximum value of 1533°F. Figure 62 shows the gas velocity adjacent to Sprinkler No. 1 for Tests S3.1 and S3.2. At the time of sprinkler activation, the gas velocity was 14.0 ft/sec for Test S3.1 and 6.5 ft/sec for Test S3.2. Maximum gas velocities for Tests S3.1 and S3.2 were 19.4 and 14.6 ft/sec respectively.

For Tests S3.1 and S3.2, the eye-level CO concentration, eye-level gas temperature, and ceiling surface temperature are shown in Figures 63, 64 and 65 respectively. The maximum CO concentration in Test S3.1 was beyond the range of the CO analyzer. The CO_2 and O_2 concentrations at eye level are presented in Figure 66. Table IX lists maximum values of CO, CO_2 concentrations, O_2 deficiency, and gas temperature at eye level; and the ceiling surface temperature. All these maximum values have exceeded the critical values adopted for evaluation of sprinkler performance. The results of Test S3.2 indicate that, in order to provide adequate life safety and property protection, a sprinkler activated by a 16.9 sec time constant link is required to deliver an application density, w_c, of more than 0.028 gpm/ft^2 to the 5-ft x 5-ft shaded area of the floor water

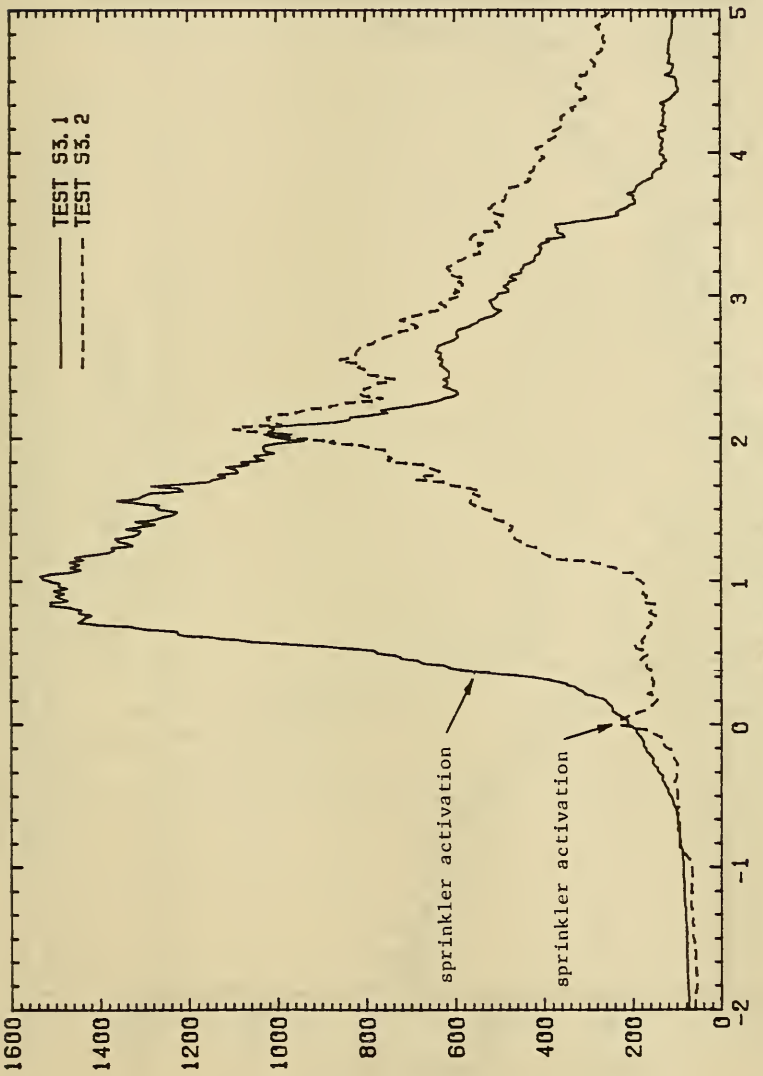


FIGURE 61 GAS TEMPERATURE ADJACENT TO SPRINKLER NO.1 - TESTS S3.1 AND S3.2
(Note : t_d' = time at which temperature of a 16.9 second time constant link would increase, or increased, by 86°F)

FIGURE 62 GAS VELOCITY ADJACENT TO SPRINKLER NO.1 - TESTS S3.1 AND S3.2
(Note: t_d'= time at which temperature of 16.9 sec time constant link would increase, or increased, by 86°F)

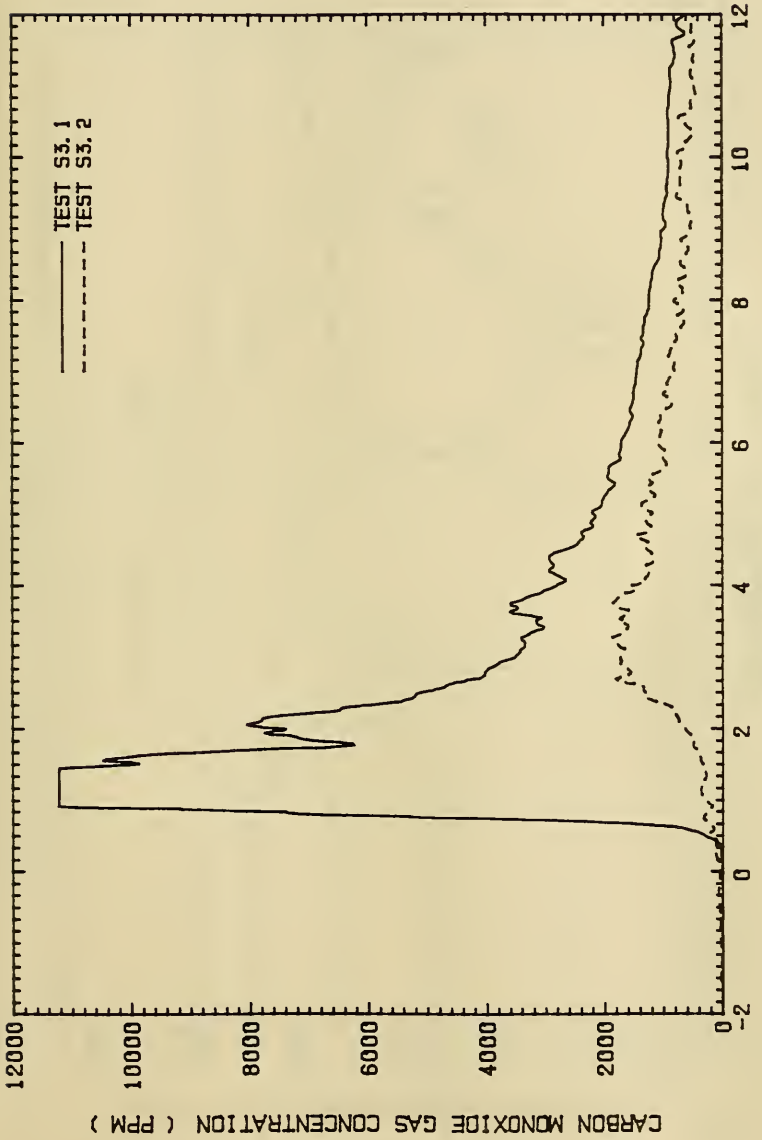


FIGURE 63 CARBON MONOXIDE GAS CONCENTRATION AT EYE LEVEL - TESTS S3.1 AND S3.2
(Note: t_d' = time at which the temperature of a 16.9 second time constant link would increase, or increased, by $86^{\circ}F$)

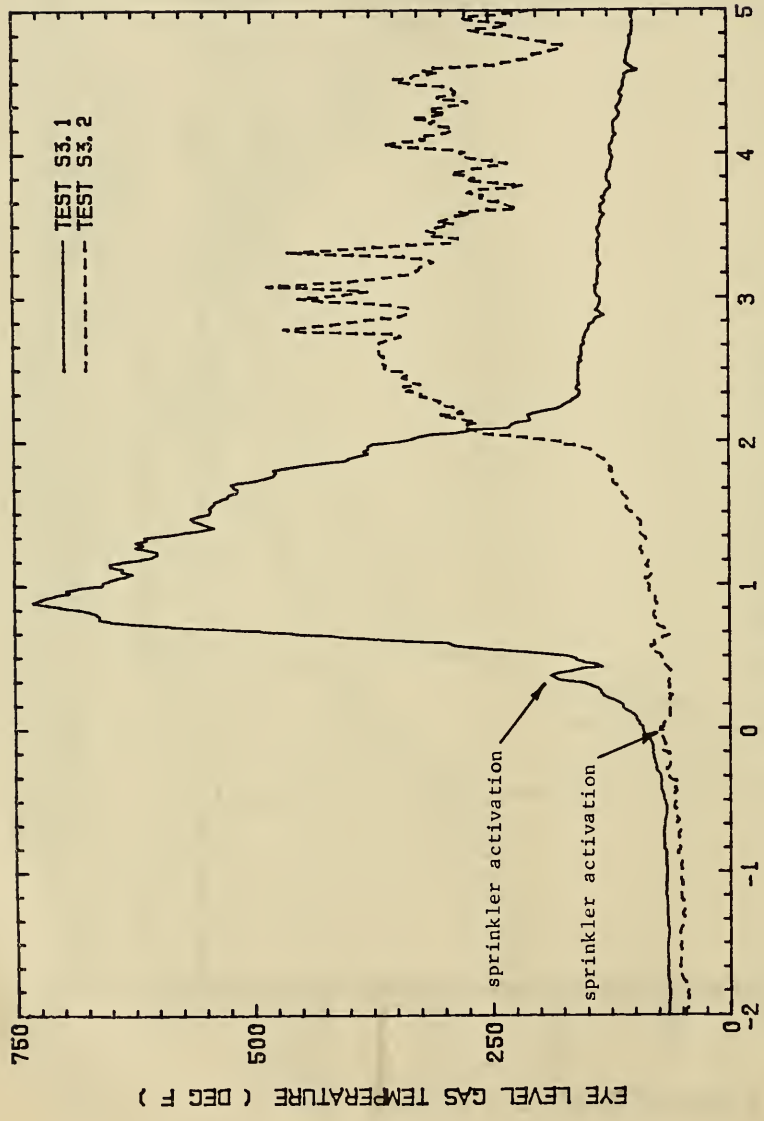


FIGURE 64 GAS TEMPERATURE AT EYE LEVEL - TESTS S3.1 AND S3.2
(Note: t_d = time at which the temperature of a 16.9 second time constant link would increase, or increased, by 86°F)

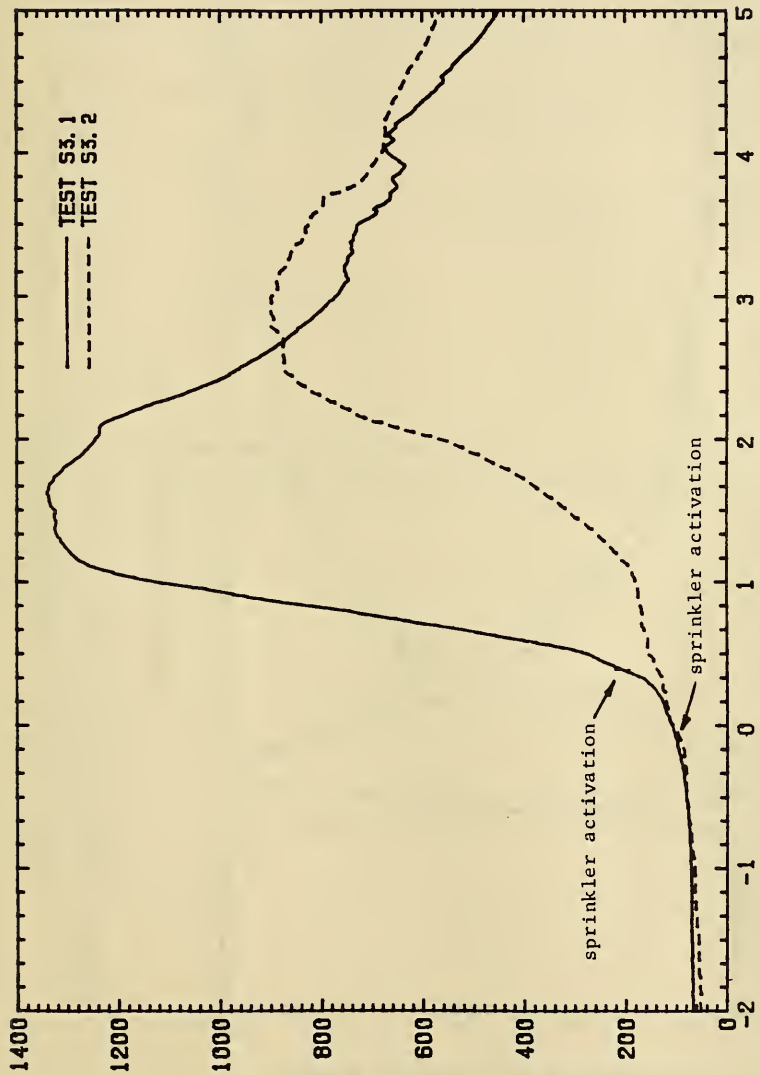


FIGURE 65 CEILING SURFACE TEMPERATURE OVER IGNITION POINT - TESTS S3.1 AND S3.2
(Note: t_d'=Time at which temperature of a 16.9 sec.time-constant link would increase,or increased,by 86°F)

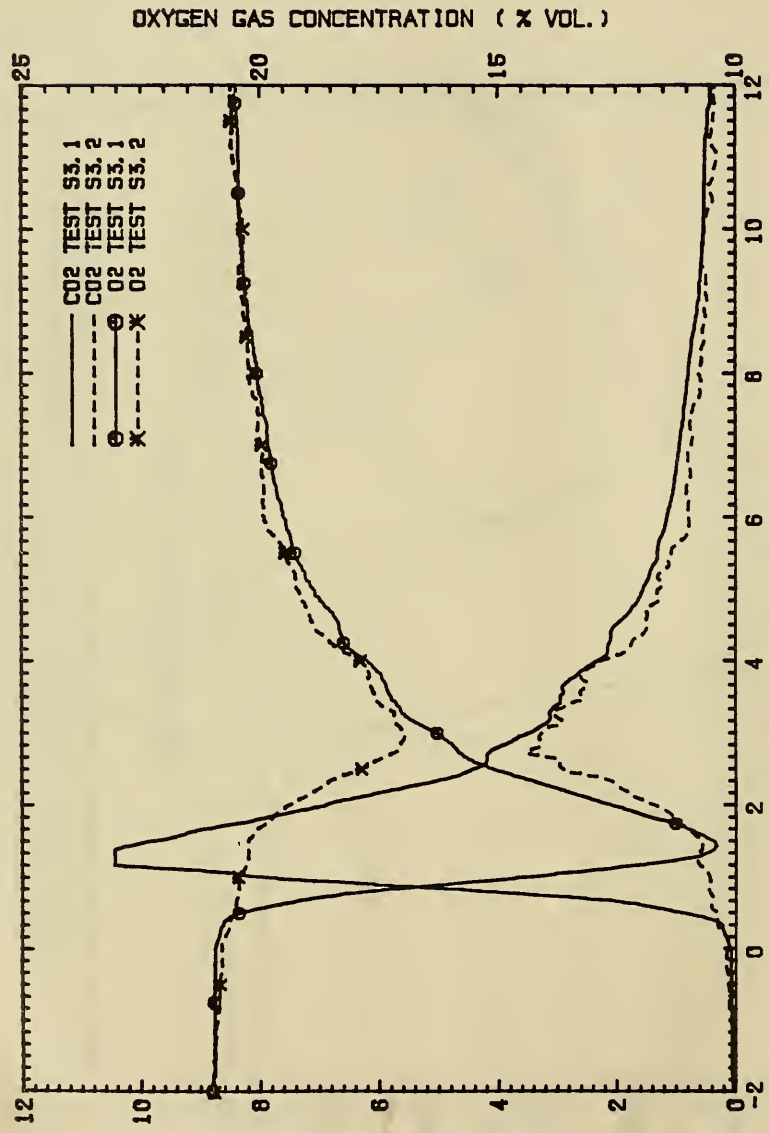

OXYGEN GAS CONCENTRATION (% VOL.)
CO2 TEST S3.1
CO2 TEST S3.2
O2 TEST S3.1
O2 TEST S3.2
CARBON DIOXIDE GAS CONCENTRATION (% VOL.)
TIME RELATIVE TO t_d' (MIN.)

FIGURE 66 CARBON DIOXIDE AND OXYGEN GAS CONCENTRATIONS AT EYE LEVEL - TESTS S3.1 AND S3.2
(Note: t_d'= time at which temperature of 16.9 sec time constant link would increase,or increased,by 86°F)

TABLE IX

MAXIMUM VALUES OF CO, CO_2 CONCENTRATIONS, O_2 DEFICIENCY AND GAS TEMPERATURE AT EYE LEVEL, CEILING SURFACE TEMPERATURE ABOVE IGNITION POINT FOR TESTS S3.1 AND S3.2

Test	S3.1	S3.2
CO (ppm)	over 10,000	1,800
CO_2 (%)	over 10	3.1
O_2 deficiency (%)	9.4	4.0
T_e (°F)	730	424
T_c (°F)	1340	900

Note: T_e: Gas temperature at eye level
T_c: Ceiling surface temperature above ignition point

distribution plan (see Figure 29), and a vertical application density, w_v, of more than 0.006 gpm/ft^2 over the 1-ft wide x 2.5-ft high area on the wall above the chair (see Figure 29), so that a sufficient amount of water can be delivered to the fire source and the wall adjacent to the fire source.

In Tests S3.3 and S3.4, experimental 0.329-in. orifice sprinklers activated by simulated link of 16.9 sec time constant were used. With one sprinkler in operation the sprinkler discharge rate was 12 gpm; at the time of second sprinkler activation, the discharge rate through each sprinkler was adjusted to 9 gpm. The experimental 0.329-in. sprinkler, operating at 12 gpm delivers a value, w_v, of 0.047 gpm/ft^2 over the 1-ft wide x 2.5-ft high area on the north wall (Figure 30b) and the average density, w_c, over the 5-ft x 5-ft shaded area of the floor water distribution plan (Figure 30a) is 0.038 gpm/ft^2. At 9 gpm, the average application density, w_c, is 0.039 gpm (Figure 31a) and the vertical application density, w_v, is 0.016 gpm/ft^2(Figure 31b).

The sprinkler variable investigated in these two tests was the difference, ΔT_d, between the rated link temperature and the initial link temperature. The temperature differences, ΔT_d, were 76°F for Test S3.3, 94°F for Test S3.4. The gas temperature and the gas velocity adjacent to Sprinkler No. 1 are shown in Figures 67 and 68 respectively. Initial gas temperatures were 67°F for Test S3.3; 69°F, for Test S3.2. The reference point of the time abscissa is the time, t''_d, at which the 16.9-sec, time-constant link increased 76°F from its initial temperature. In Test S3.3, at time, t''_d, the link temperature reached its rated value, 143°F, and the gas temperature and the gas velocity were 177°F and 7.9 ft/sec respectively. In Test S3.4, at time, t''_d, the gas temperature was 194°F and the gas velocity was 8.2 ft/sec. Three sec after t''_d, the link temperature reached its rated value, 163°F, the gas temperature increased from 193°F to 253°F and the velocity increased from 8.2 ft/sec to 10.2 ft/sec. At the time of first sprinkler activation, in Test S3.3, flames along the curtains behind the chair only reached half the curtain height, whereas in Test S3.4, flame along the curtains started to touch the ceiling.

For Tests S3.3 and S3.4 Figure 69 shows the thermal responses of the three 16.9-sec time constant simulated links located: 1) adjacent to Sprinkler No. 1; 2) adjacent to Sprinkler No. 2; and 3) in the hallway. The link temperature dropped abruptly as sprinkler water impinged on the link at the time of sprinkler

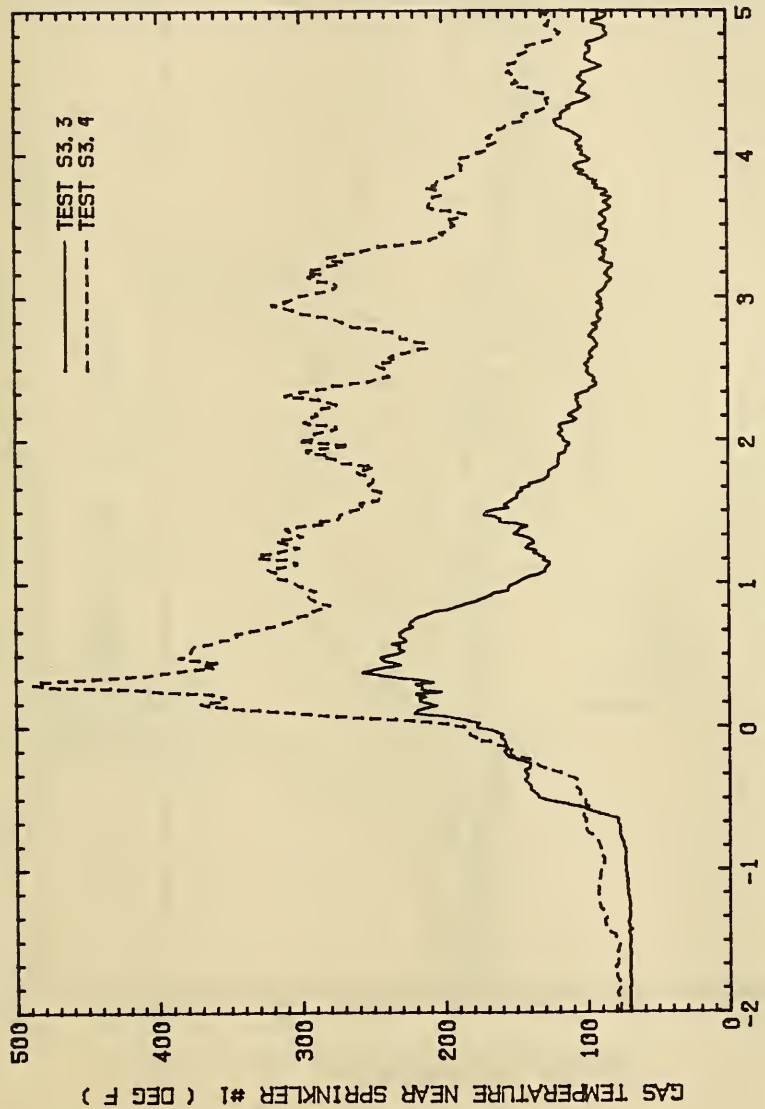


FIGURE 67 GAS TEMPERATURE ADJACENT TO SPRINKLER NO.1 - TESTS S3.3 AND S3.4
(Note : t_d''=time at which temperature of 16.9 second time constant link would increase,or increased,by 76°F)

FIGURE 68 GAS VELOCITY ADJACENT TO SPRINKLER NO.1 - TESTS S3.3 AND S3.4
(Note : t_d'= time at which the temperature of a 16.9 second time constant link would increase,or increased,by 76°F)

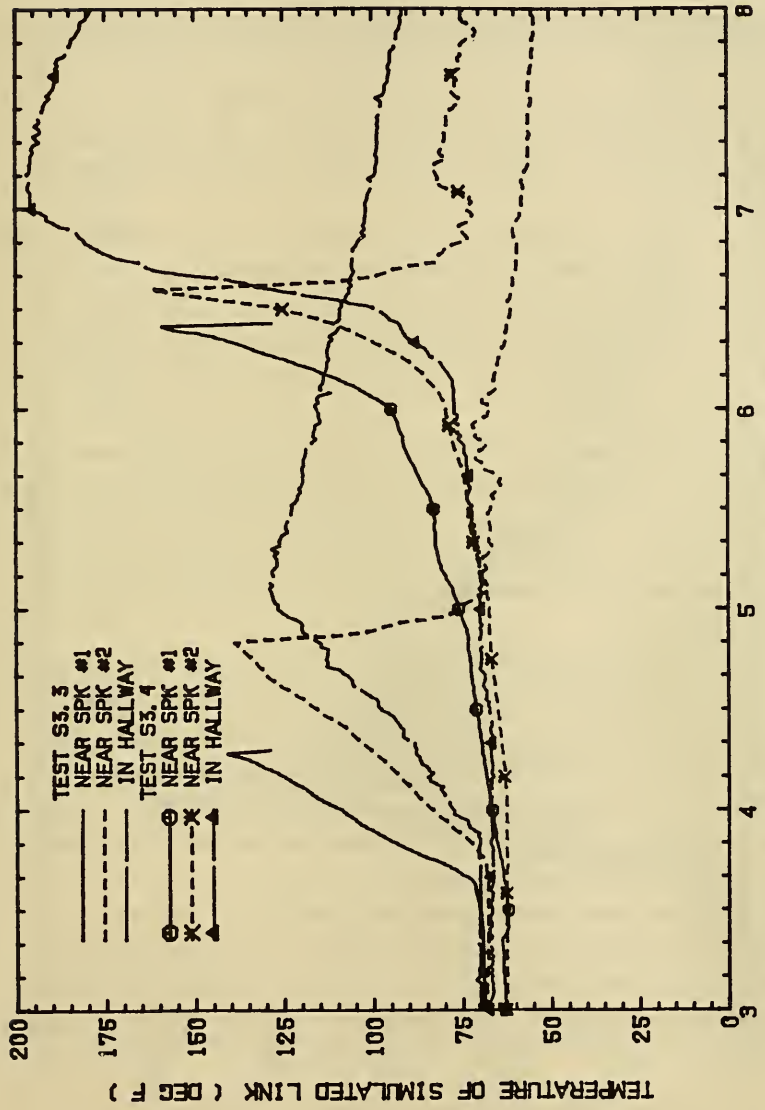


FIGURE 69 TEMPERATURE OF THREE STIMULATED LINKS LOCATED AT SPRINKLERS NO. 1 AND NO. 2 AND IN HALLWAY - TESTS S3.3 AND S3.4

activation. The duration between the first and second sprinkler activations were 33 and 11 sec for Tests S3.3 and S3.4 respectively. In Test S3.4, the link in the hallway exceeded the rated temperature 162°F 7 sec after the second sprinkler activation. In Test S3.3, the maximum temperature of the link in the hallway was 131°F, which was less than the link temperature rating 143°F. These results indicate that using links of the same sensitivity, the higher temperature-rating links would cause a larger fire and smaller time interval between sprinkler activations.

For Tests S3.3 and S3.4, the eye-level CO concentration, eye-level gas temperatures and ceiling surface temperature are shown in Figures 70, 71 and 72 respectively. The maximum values of CO, CO_2 concentrations, O_2 deficiency, and gas temperature at eye level and ceiling surface temperature are listed in Table X. All these values are smaller than the critical values adopted for sprinkler performance evaluation.

The application densities, w_v, over the 1-ft wide x 2.5-ft high area on the wall above the chair of the experimental 0.329-in. sprinkler at 12 and 9 gpm are 0.047 and 0.016 gpm/ft^2 respectively. In both Tests S3.3 and S3.4, the plywood panel behind the chair was only slightly discolored. Damage was limited to the chair, the curtains on the northeast wall, the end table and the carpet (Tables A-9 and A-10).

Hence, sprinklers activated by 16.9-sec time-constant links rated at 163°F or below, delivering an application density, w_c, of more than 0.038 gpm/ft^2 and a vertical application density w_v, of more than 0.016 gpm/ft^2 have been demonstrated to be capable of providing adequate life-safety and property protection in such a high-challenge, fast-developing, ventilated fire. With 143°F links, the total water demand for the sprinkler system was 18 gpm; when 163°F links were used, the total water demand was 27 gpm.

These tests with the experimental sprinklers have made it possible to determine the application density over the fire source, w_c, and the vertical application density on the wall above the fire source, w_v, required to control the high-challenge, fast-developing, ventilated fire. The test results indicate

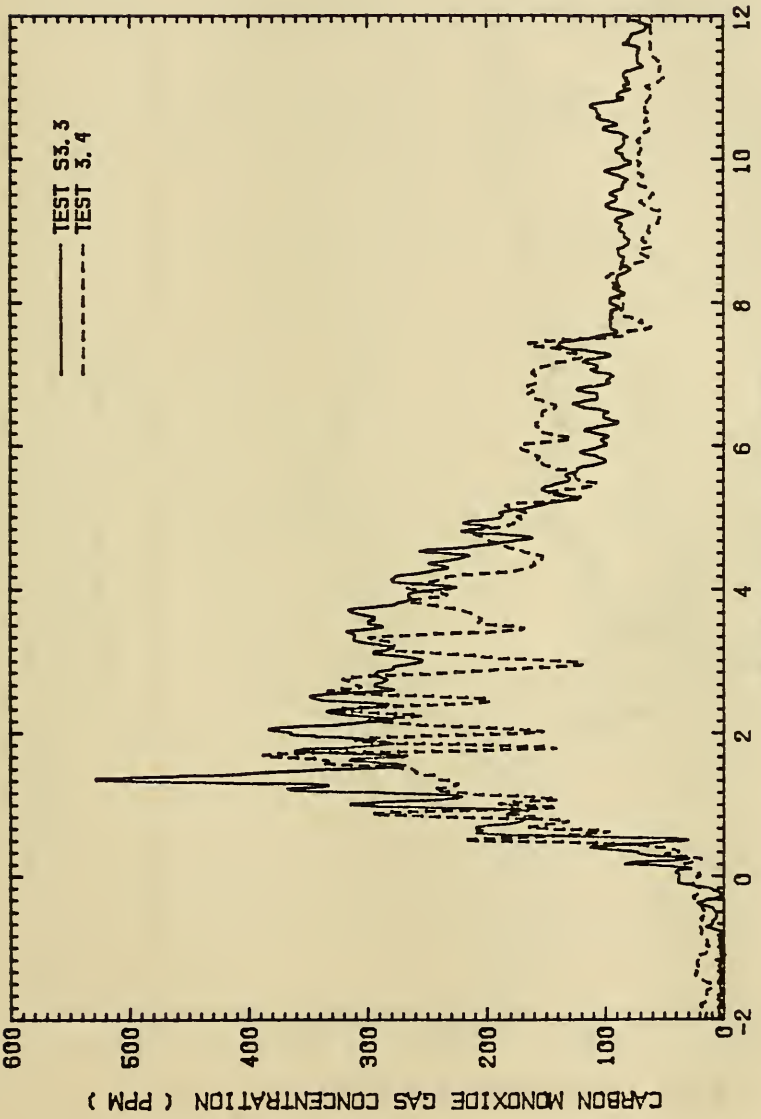


FIGURE 70 CO GAS CONCENTRATION AT EYE LEVEL - TESTS S3.3 AND S3.4
(Note: t_d'=time at which temperature of 16.9 second time constant link would increase,or increased,by $76^{o}F$)

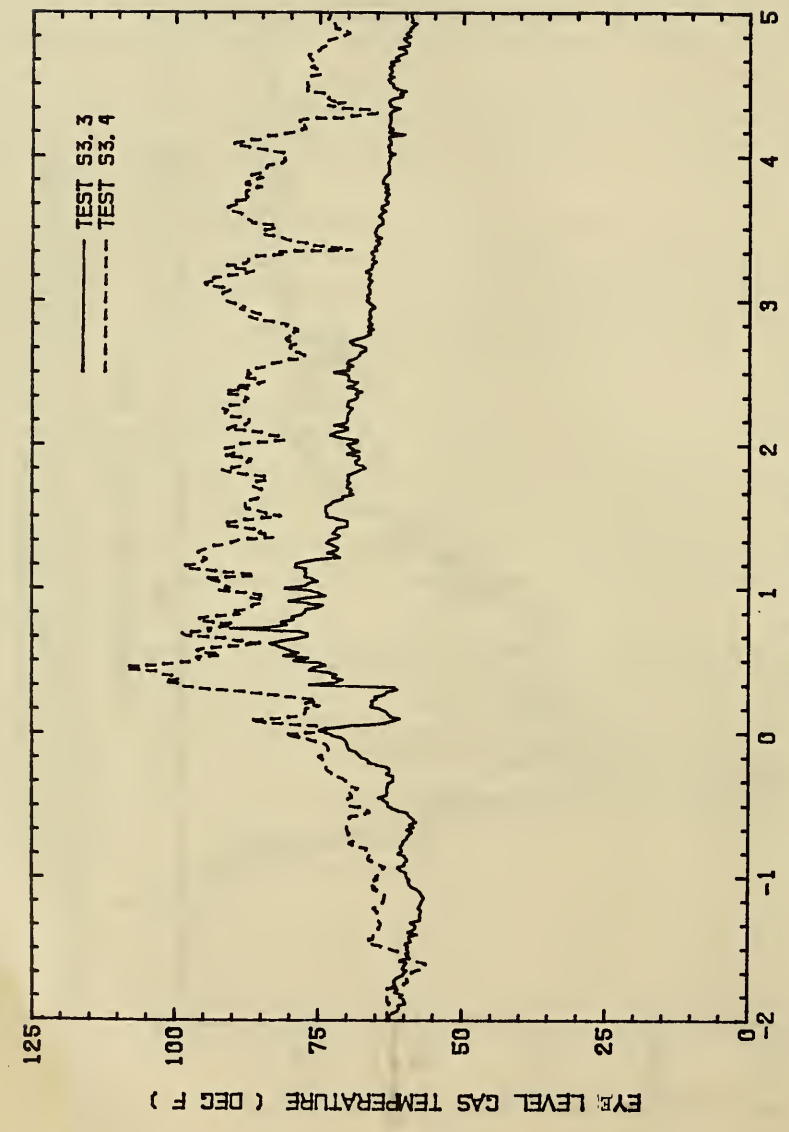


FIGURE 71 GAS TEMPERATURE AT EYE LEVEL - TESTS S3.3 AND S3.4
(Note: t_d''=time at which the temperature of a 16.9 second time constant link would increase,or increased,by $76^{o}F$)

FIGURE 72 CEILING SURFACE TEMPERATURE - TESTS S3.3 AND S3.4
(Note: t_d"=time at which the temperature of a 16.9 second time constant link would increase, or increased, by 76°F)

TABLE X

MAXIMUM VALUES OF CO, CO_2 CONCENTRATIONS, O_2 DEFICIENCY, AND GAS TEMPERATURE AT EYE LEVEL; AND CEILING SURFACE TEMPERATURE ABOVE IGNITION POINT FOR TESTS S3.3 AND S3.4

Test	S3.3	S3.4
CO (ppm)	500	390
CO_2 (%)	0.6	1.1
O_2 deficiency (%)	0.9	0.9
T_e (°F)	90	109
T_c (°F)	195	260

Note: T_e: Gas temperature at eye level

T_c: Ceiling surface temperature above ignition point

that, using a high sensitivity link of 16.9 sec time constant, rated at 163°F or below, the required value of w_c is between 0.028 to 0.038 gpm/ft^2, and the required value of w_v is between 0.006 to 0.016 gpm/ft^2.

Two different kinds of manufacturer's prototype sprinklers were used in the test program. The spray patterns of these sprinklers had no apparent voids behind the arms of the sprinkler frame. Manufacturer's prototype 1, operating at 12 or 9 gpm delivers water to the walls at a height within 1 ft from the ceiling (Figures 32 and 33). Operating at 12 gpm, this sprinkler had an application density, w_c, of 0.028 gpm/ft^2 and a vertical application density, w_v, of 0.012 gpm/ft^2 (Figure 32); at 9 gpm, the values of w_c and w_v are 0.027 gpm/ft^2 and 0.012 gpm/ft^2 respectively (Figure 33). For manufacturer's prototype 2, at 15 gpm, the average application density, w_c, is 0.035 gpm/ft^2 and the vertical application density, w_v, is 0.012 gpm/ft^2 (Figure 34). With regard to water distribution, these prototypes meet the distribution brackets described in the previous paragraph, although for prototype 1 the value of w_c was on the borderline. Furthermore, each prototype sprinkler was equipped with a sprinkler valve assembly and a link-lever releasing device, the sprinkler link having a 15.1 sec time constant and rated at 136°F, both implying faster response than the simulated link referred to in the previous paragraph.

Manufacturer's prototype 1 was investigated in Test S3.5. With one sprinkler in operation, the sprinkler discharge rate was 12 gpm; when the second sprinkler was activated, the discharge rate through each sprinkler was 9 gpm. Although the water application density on the wall above the chair was adequate to stop the fire from jumping from the backside of the chair to the wall, the application density over the fire source, w_c, was not sufficient to prevent the fire source from igniting the ceiling above the fire and the plywood panels above the windows. Damage was quite extensive. Evidently, the density, w_c, was not sufficient.

Manufacturer's prototype 2 was investigated in Tests S3.6 and S3.7. The discharge rate of the first sprinkler was set at 15 gpm. In both tests, only one sprinkler was activated. An adequate amount of water was delivered over the fire source and to the walls. The fire was controlled and the major burning was limited to the chair.

Gas concentrations of CO, CO_2, and O_2 at eye level for Test S3.5 are shown in Figure 73. The maximum values of CO and CO_2 concentrations and O_2 deficiency

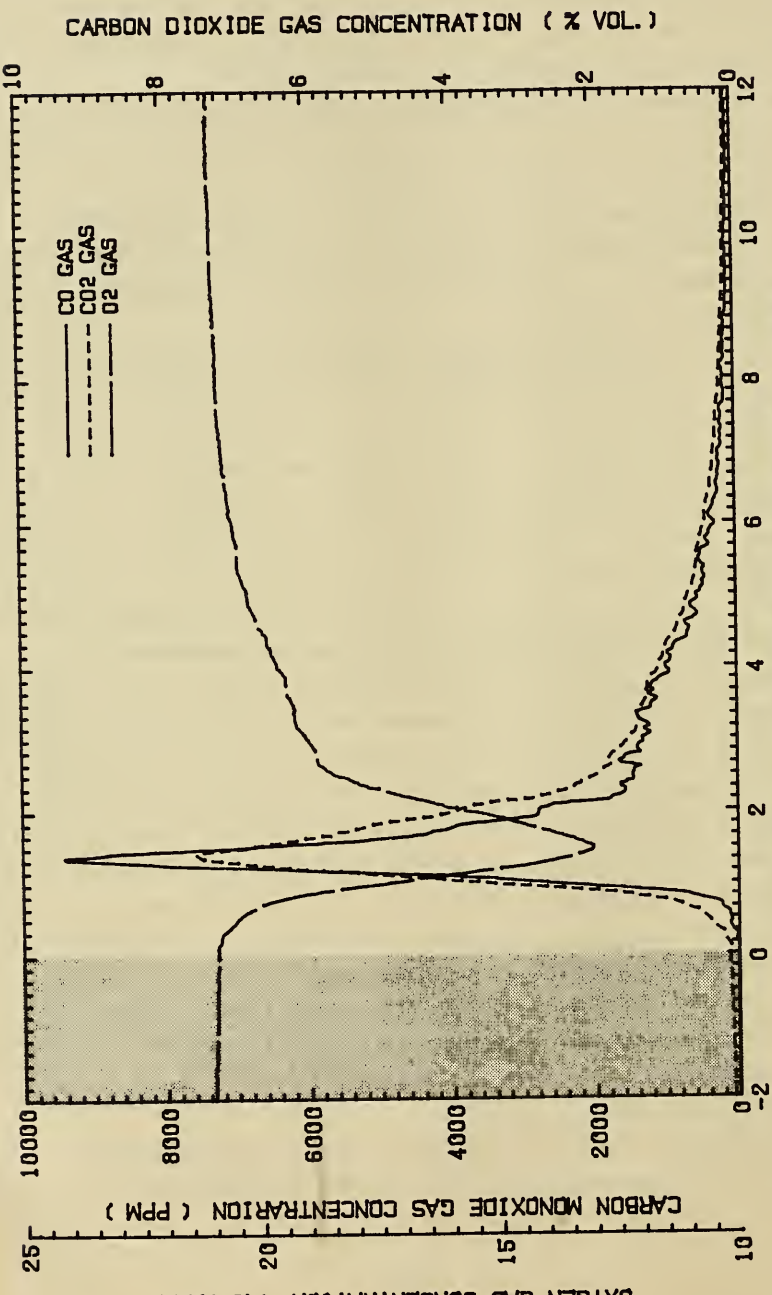

CARBON DIOXIDE GAS CONCENTRATION (% VOL.)
CO GAS
CO2 GAS
O2 GAS
TIME RELATIVE TO SPRINKLER ACTIVATION t_s (MIN.)
CARBON MONOXIDE GAS CONCENTRATION (PPM)
OXYGEN GAS CONCENTRATION (% VOL.)

FIGURE 73 GAS CONCENTRATIONS OF CO, CO_2 AND O_2 AT EYE LEVEL - TEST S3.5

were 9400 ppm, 8.0 percent, and 8.9 percent respectively. Based on measurements of CO, CO_2 and O_2 concentrations, the environment in the room of fire origin is deemed nonsurvivable.

Figure 74 shows the CO gas concentrations at eye level for Tests S3.6 and S3.7. In both tests, the CO concentration had not exceeded 280 ppm.

For Tests S3.5, S3.6 and S3.7, eye-level gas temperature and ceiling surface temperature above ignition are shown in Figures 75 and 76 respectively. The maximum values of CO and CO_2 concentrations, O_2 deficiency, eye-level gas temperature and ceiling surface temperature are listed in Table XI. The maximum values for Test S3.5 exceeded the adopted critical values for evaluation of sprinkler performance. However, for both Tests S3.6 and S3.7, all the maximum values were considerably smaller than the critical values. Therefore, a manufacturer's prototype sprinkler, activated by a 15.1-sec time-constant link rated at 136°F, delivering 0.035 gpm/ft^2 of w_c over the fire source in the corner of the room and 0.012 gpm/ft^2 of w_v to the wall above the chair has been demonstrated to be effective in controlling such a high-challenge, fast developing fire and capable of providing adequate life-safety and property protection in the room of fire origin.

Maximum values of gas temperature 5 13/16 in. beneath the top edge of the northwest window, and gas temperatures in the entry door 10 in. beneath the top door post and 55 in. from the floor are listed in Table XII. For Test S3.1, the potential of fire spread to the exterior combustible structure and the rest of the building was very high and the environment of the egress route through the door was not maintained survivable for occupants to be rescued or to escape. For Tests S3.2 and S3.5, the potential of fire spread to the exterior structure was quite high, and the gas temperatures in the egress area through the entry door were not maintained below the adopted critical value, 200°F for eye-level gas temperature. For the remainder of the tests in Test Series 3 (S3.3, S3.4, S3.6 and S3.7), sprinklers restricted the fire effectively to the initial burning items and the egress area was maintained survivable throughout the entire test period.

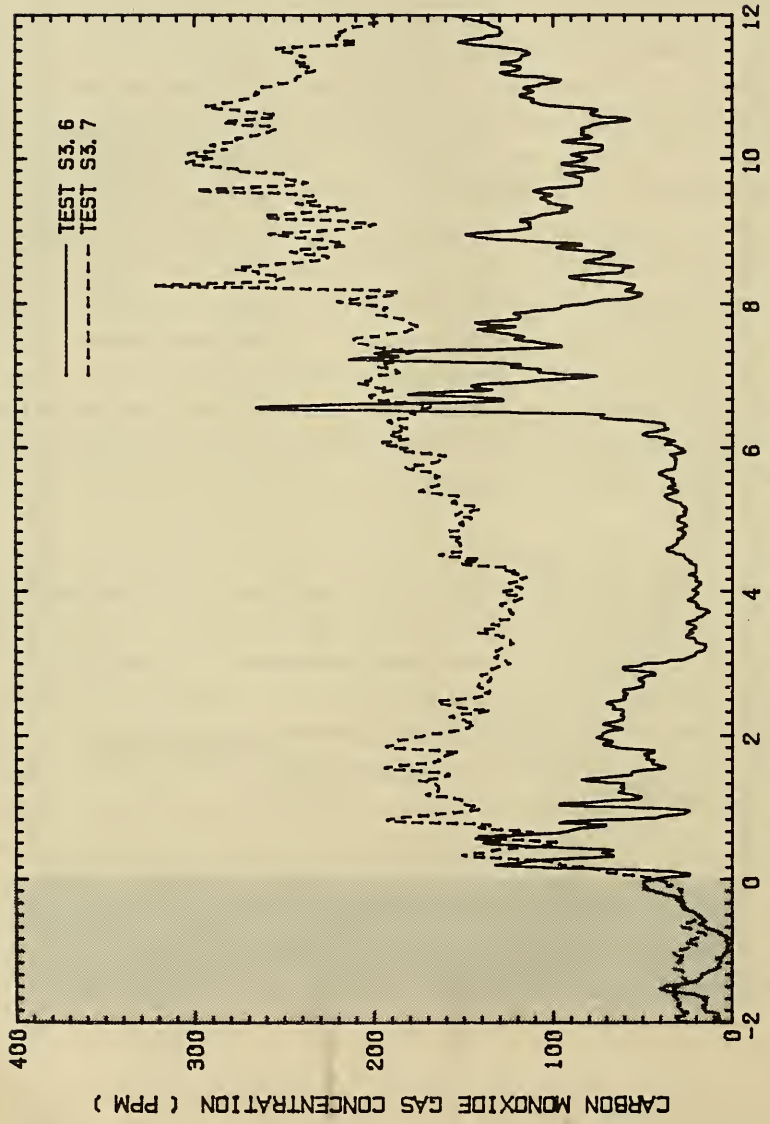


FIGURE 74 CO GAS CONCENTRATIONS AT EYE LEVEL - TESTS S3.6 AND S3.7

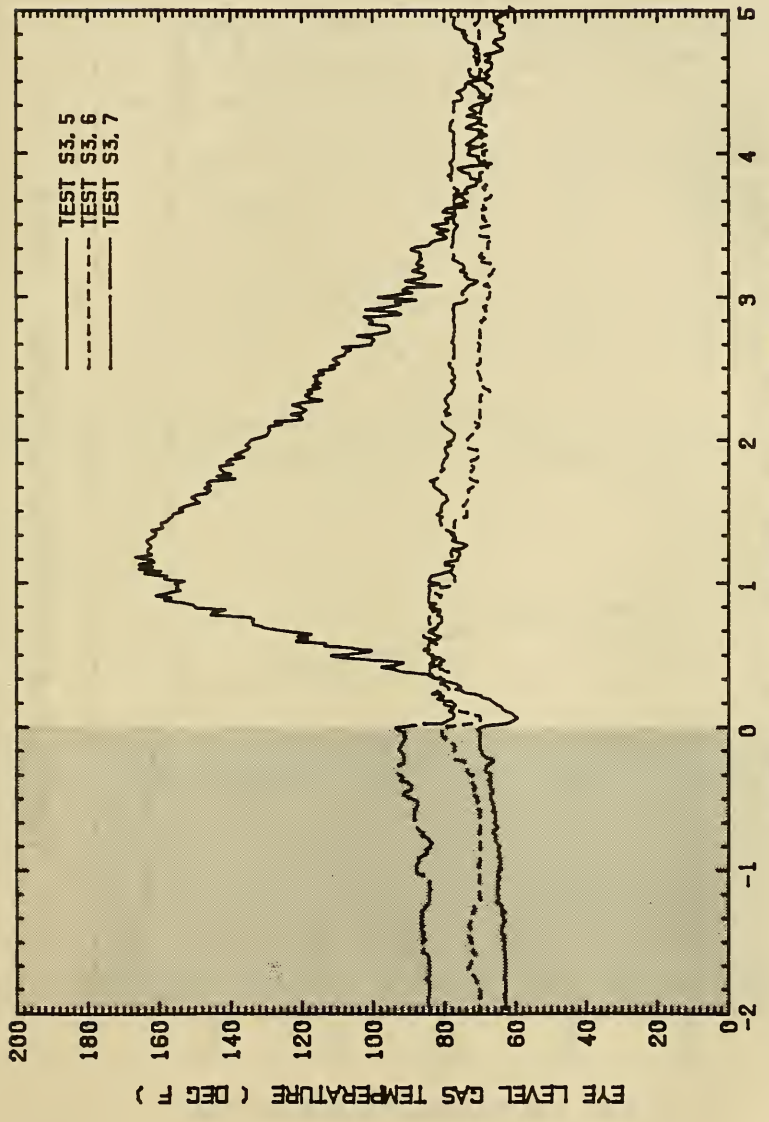


FIGURE 75 GAS TEMPERATURE AT EYE LEVEL - TESTS S3.5, S3.6, AND S3.7

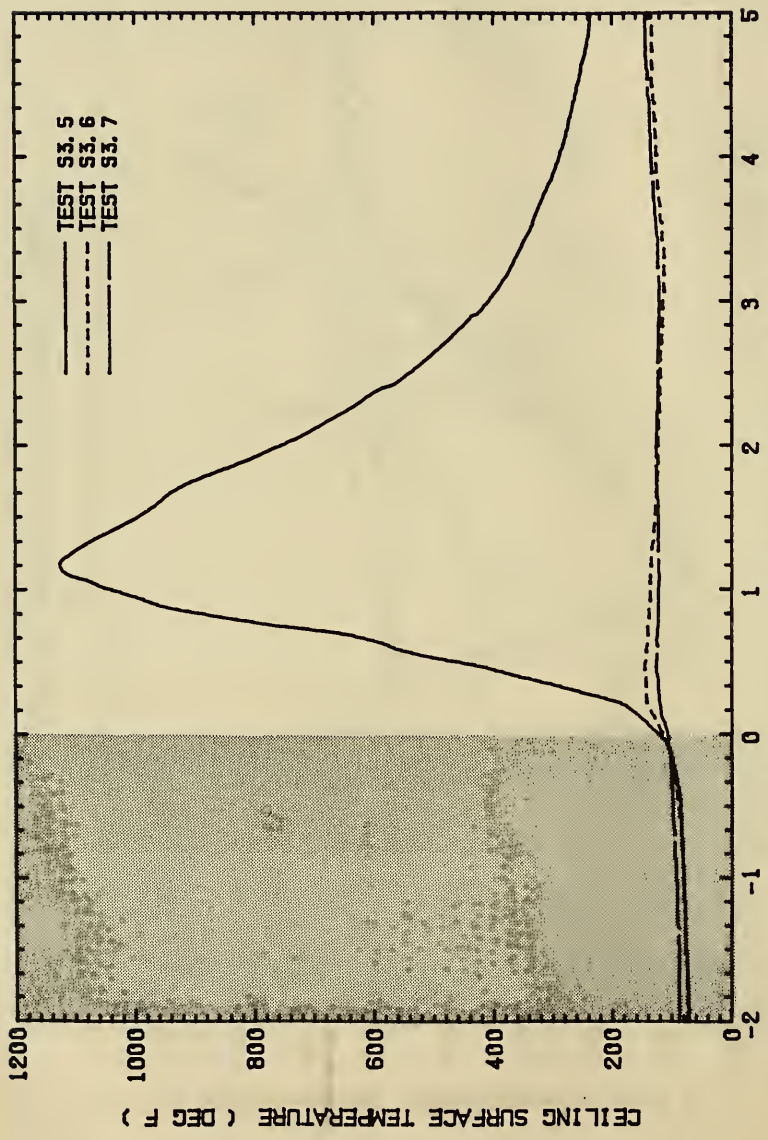


FIGURE 76 CEILING SURFACE TEMPERATURE OVER IGNITION POINT - TESTS S3.5, S3.6, AND S3.7

TABLE XI

MAXIMUM VALUES OF CO, CO_2 CONCENTRATIONS, O_2 DEFICIENCY, AND GAS TEMPERATURE AT EYE LEVEL; AND CEILING SURFACE TEMPERATURE ABOVE IGNITION POINT FOR TESTS S3.5, S3.6 AND S3.7

Test	S3.5	S3.6	S3.7
CO (ppm)	9400	200	290
CO_2 (%)	7.6	0.6	0.8
O_2 deficiency (%)	8.0	0.5	0.9
T_e (°F)	167	86	94
T_c (°F)	1125	147	183

Note: T_e: Gas temperature at eye level
T_c: Ceiling surface temperature above ignition point

TABLE XII

MAXIMUM VALUES OF GAS TEMPERATURES IN THE NORTHWEST WINDOW AND THE ENTRY DOOR FOR TEST SERIES 3

Test	S3.1	S3.2	S3.3	S3.4	S3.5	S3.6	S3.7
T_w (°F)	1115	657	103	297	843	102	99
T_{dh} (°F)	506	400	130	215	376	103	114
T_{de} (°F)	346	264	103	156	222	81	94

Note: T_w : Gas temperature in the northwest window, 5 13/16 in. beneath the window top edge

T_{dh}: Gas temperature in the entry door, 10 in. beneath the top door post

T_{de}: Gas temperature in the entry door, 55 in. from floor

VII
CONCLUSIONS

Performance of pendent sprinklers as affected by sprinkler link sensitivity, link temperature rating, and sprinkler water distribution has been investigated in several typical, residential fire scenarios involving flaming fire starts. The fire scenarios selected were: 1) nonventilated bedroom fire; 2) nonventilated small-bedroom fire; 3) nonventilated living room fire; 4) ventilated living room fire with noncombustible walls and ceiling; and 5) ventilated living room fire with combustible walls and ceiling.

Commercially available sprinkler links, representative of the most sensitive on the market, were employed for sprinkler activation in all the nonventilated fire tests and three of the ventilated living room fire tests. In the nonventilated small-bedroom fire, due to the small room size (12.3 ft x 8.8 ft), hot ceiling gases descended quickly to eye level. At the time of sprinkler activation, the eye-level gas temperature near the center of the room had already reached 241°F, exceeding the adopted critical value for eye-level gas temperature. In order to maintain a survivable environment in the room of fire origin throughout this fire, it was concluded that the sprinkler should respond at an earlier stage of the fire; in other words, the sprinkler link must be even more sensitive than the commercially available link. In the other nonventilated fires, bedroom and living room, the environment was deemed survivable at the time of sprinkler activation because of the larger room sizes.

In the ventilated fires, all in the living room, some of the hot ceiling gases escaped to the outside through windows and the door; in order to fuse a sprinkler link of the same type as used in the nonventilated living room fire, the fires had to grow to a larger size than in the nonventilated living room fire. In addition, the ventilated fire developed at a much higher rate than fire without ventilation. At the time the commercial link fused, the fire was already in its very fast accelerating stage; the entire furnished corner of the room was engulfed in flames; and flames swept across the ceiling. In order to have a somewhat safer environment at the time of sprinkler activation in the ventilated living room, it was deemed necessary to employ a more sensitive link than the commercial link, as in the nonventilated small-bedroom fire.

The bedroom fire was initiated at the side of the bed. Since the bed fire was not shielded from sprinkler spray, a local water application density of 0.02 gpm/ft^2 on the fire source was demonstrated to be adequate in suppressing the fire.

In the living room fire tests, combustibles were located in the northeast corner of the room; fire first spread to the left side of a reclining chair, and then to the curtains behind the chair. Fire on the left side and backside of the chair was shielded from direct sprinkler water impingement. In order to suppress such a challenging fire and cool the fire gases, considerably more water was required over the fire source than in the bedroom fire. An average water application density, w_c, over a 5-ft x 5-ft floor area in the corner of a 15-ft x 15-ft coverage area without walls was used to indicate the amount of sprinkler water delivered to the corner of the living room. The vertical application density, w_v, over the 1-ft wide x 2.5-ft high area on the wall above the chair indicates the amount of water delivered to protect the wall from igniting by the source fire.

In the nonventilated living room fire with combustible walls and ceiling, the sprinkler, delivering an average application density, w_c, of 0.015 gpm/ft^2, was not capable of suppressing the fire and cooling the gases sufficiently. Judging from the ceiling gas temperature and velocity measurements in the living room, it is expected that the sprinklers in the hallway and kitchen would have actuated. Although the application density, w_c, was not sufficient, the combustible ceiling tile and panel above the window did not ignite, due to lower heat release rate in the nonventilated fire. With regard to the vertical application density, w_v, a value of 0.011 gpm/ft^2 delivered by the sprinkler was sufficient to prevent fire spread to the wall.

In the ventilated living room fire tests with noncombustible walls and ceiling, it was demonstrated that by reducing the sprinkler link response time less water was required to control the fire. A sprinkler activated by a 16.9-sec time constant link rated at 140°F, delivering an application density, w_c, of 0.015 gpm/ft^2, was capable of providing adequate life-safety and property protection in the room of fire origin. However, a value of w_c of 0.015 gpm/ft^2 was not sufficient to suppress the fire and cool the fire gases to prevent excessive sprinkler openings in the hallway and the kitchen outside the living room.

In the ventilated living room fire tests with combustible walls and ceiling, at the time of sprinkler activation with the commercial link, the fire had already begun to spread to the plywood panels and flames were sweeping across the ceiling. It was even more critical in such fires to use a more sensitive link to activate the sprinkler at the time when the major burning activity was still limited to the chair.

Using a high-sensitivity simulated link of 16.9 sec time constant, tests with experimental sprinklers have made it possible to bracket the application density over the fire source, w_c, and the vertical application density, w_v, required to control the ventilated living room fire.

Manufacturer's prototypes with a link of 15.1-sec time constant rated at 136°F were subsequently investigated in the same ventilated living room fire tests. The critical value of the application density, w_c, was found to be 0.035 gpm/ft^2 in order to suppress the fire source in the corner and prevent plywood panels and the combustible ceiling above the fire source from igniting. In addition, sufficient wetting of the combustible walls was also essential in preventing fire spread from the fire source to the walls. A vertical application density, w_v, of 0.012 gpm/ft^2 on the wall from 3.5 ft to 6 ft from the floor was demonstrated to be adequate to prevent fire jump from the backside of the chair to the wall.

In the tests in which the manufacturer's prototype 2 sprinkler was demonstrated to be successful in controlling such a challenging ventilated fire, only one sprinkler was activated and the sprinkler discharge rate was 15 gpm covering a 12-ft x 12-ft area. Further, the prototype discharges a rather uniform pattern in the angular distribution so that, even if a fire starts behind the arms of the sprinkler frame, an adequate amount of water can be expected to be delivered to the fire source.

In conclusion, significantly more sensitive links than the commercial link representative of the most sensitive on the market are essential in providing adequate life-safety and property protection in residential fires. The required sprinkler operation conditions for control of such a typical high-challenge, fast-developing residential fire have been determined in terms of water distribution associated with a link (rated at 136°F) five times as sensitive as the commercial link.

The results obtained in the program will 1) serve as a guide for the development of residential sprinklers, 2) establish a foundation for new installation standards of residential sprinkler systems, and 3) lead to new evaluation standards for approval and listing by recognized laboratories.

VIII

RECOMMENDATIONS

This study has been concerned with sprinkler performance in residential fires only as affected by link sensitivity, link temperature rating, and water distribution. The aspect of spray cooling of fire gases in preventing excessive sprinkler operations has not been addressed. Optimization of the cooling effect will reduce the likelihood of excessive sprinkler openings, and will enhance system reliability. With only one or two sprinklers closest to the fire in operation, the total water demand required should be within the limit of the domestic water supply. Consequently, affordable residential sprinkler systems can be realized.

A fire initiated under a sprinkler would activate the sprinkler earlier than a fire initiated in the corner farther from the sprinkler. In addition, since the corner fire is much more challenging, it is believed that the water application density required to control a fire underneath the sprinkler would be less than that for a corner fire. Therefore, improvement in sprinkler water distribution of manufacturer's prototype 2 sprinklers presumably can be made with less water delivered to the area under the sprinkler, and more water to the periphery of the room and the walls.

Water delivered to the wall at a height close to the ceiling not only protects the portion of the wall close to the ceiling but also enhances the spray cooling ability of the ceiling gases to reduce the likelihood of excessive sprinkler openings. It is desirable to have a wider spray pattern than that of the manufacturer's prototype 2.

Therefore, emphasis is recommended in future programs on the following aspects of residential sprinkler technology: 1) investigation of the effect of sprinkler cooling of fire gases in preventing excessive sprinkler openings; and 2) development of residential sprinklers with improved water distribution patterns.

From the point of view of system cost, sidewall sprinkler systems have an advantage over pendent sprinkler systems, especially for installations in existing residences where it is much easier to install a sidewall sprinkler system. The information gained in this program can be used as a base for the

research and development of residential sidewall sprinklers. Research to determine the required link sensitivity, spray pattern, and spray cooling of sidewall sprinklers in controlling high-challenge residential fires is essential.

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APPENDIX A

OBSERVATIONS

A log of visual observations and damage assessments is provided for each of the fire tests in Tables A.1 - A.13. Pictorial histories (Figures A.1 - A.12) prior to sprinkler operation of Test Series 1, Test Series 2, and Tests S3.1, S3.2, S3.3, S3.4, S3.6, S3.7 accompany the observations. Post-test appearances of Tests S1.1, S1.2, S1.3, S2.2, S3.3 and S3.6 are shown in Figure A.13.

TABLE A-1

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S1.1

Time (min:sec)	Observations
0:00	Ignition
0:10	Small flame at bottom right side of bedspread
0:20	Flames at bottom of bedspread 1 ft wide and 1 ft high
0:27	Flames at 3-ft level; right side of headboard starting to char
0:42	Light smoke accumulating in upper half of room
0:49	Flames at 4-ft level
1:04	Flames diminishing
1:15	Dense smoke accumulating
1:22	Flames at 3-ft level and burning along mattress edge creeping toward foot of bed; flames penetrated 6 in. into bedspread, mattress and pillow; headboard also burning
1:50	Dense smoke throughout room
1:57	Sprinkler activation
2:05	Flames diminishing
2:10	Flames under right side of bed, 3 ft down from headboard
2:30	Very dense smoke
2:50	Small fire 2 ft down from headboard
3:10	Visibility obscured; small fire right side of bed
3:20	Fire appears to be out
4:00	Very dense smoke

Post-Test Fire Damage Assessment

Carpet: 1-ft dia hole burned through directly under ignition point

Bedding: Bedspread, blanket, top sheet and bottom sheet consumed 4.5 ft toward foot of bed and 1 ft toward center of bed from ignition point and tapered off toward foot of bed

Pillow Near Ignition: Cloth burned through exposing inside pillow

Pillow Away from Ignition: Cloth covering charred

Mattress: Near ignition a section 2 ft long and 6 in. deep into mattress was burned

a) 107 sec before sprinkler activation

b) 72 sec before sprinkler activation

c) 40 sec before sprinkler activation

FIGURE A.1 PICTORIAL HISTORY OF FIRE TEST S1.1

TABLE A-2

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S1.2

Time (min:sec)	Observations
0:00	Ignition
0:10	Light smoke rising between bed and wall
0:23	Flames at bottom left side of bed 18 in. from headboard
0:34	Flames at 3-4 ft level
0:45	Fire creeping toward foot of bed and toward pillow
1:00	Smoke accumulating throughout room
1:20	Fire appears to be burning under bed
1:30	Fire progressed 4 ft away from headboard
1:40	Dense smoke, visibility obscured
2:05	Sprinkler activation
2:08	Water from sprinkler diminished fire
2:15	Dense smoke, fire observed on left side and halfway down bed
2:20	Small fire left side of bed
2:40	Small fire persisting at bottom left side of bed
2:53	Fire is not visible
10:00	Dense smoke, no sign of fire

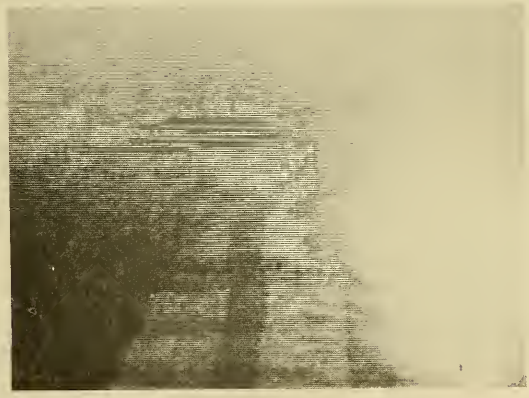
Post-Test Fire Damage Assessment

Carpet:	1-ft dia hole burned through directly under ignition point
Bedding:	Blanket and sheets burned on the side of bed at ignition point; burn area from head of bed toward foot, with little damage at foot of bed
Pillow:	Pillow and pillow case burned on side of ignition
Mattress:	Underneath mattress covering was consumed
Wood Frame:	Charred on side near ignition

a) 30 sec before sprinkler activation
ΔTg = 184°F

b) 20 sec before sprinkler activation
ΔTg = 196°F

c) 10 sec before sprinkler activation
ΔTg = 206°F



d) sprinkler activation
ΔTg = 230°F

ΔTg = Tg - Tgo
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 77°F

FIGURE A.2 PICTORIAL HISTORY OF FIRE TEST S1.2

TABLE A-3

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S1.3

Time (min:sec)	Observations
0:00	Ignition
0:10	Light smoke coming from wastebasket
0:30	Visible fire in wastebasket
0:45	Flames under left side of end table
0:55	Flames increasing
1:00	Light smoke at ceiling level
1:10	Fire melting plastic wastebasket
1:20	Light smoke layer 1 ft below ceiling
1:35	Wastebasket falling toward vinyl covered chair
2:00	Medium smoke at ceiling to very light smoke at 4-ft level
2:25	Fire burning under end table, table not ignited; fire approaching vinyl chair
2:50	Wastebasket burning
3:05	Lower left side of vinyl chair starting to burn
3:45	Bottom left side of vinyl chair slowly burning; fire under end table
4:15	Light smoke throughout room
5:00	Left side of vinyl chair burning at arm rest level
5:30	Light smoke throughout room; fire creeping up left side of vinyl chair
5:45	Medium smoke throughout room
5:55	Complete left side of vinyl chair burning
6:20	End table charring has not ignited
6:40	Fire is creeping into back rest 5-6 in. deep
7:05	Very dense smoke; flames observed; outline of chair visible
7:19	Sprinkler activation
7:30	Very dense smoke throughout room; fire burning left side of vinyl chair
7:45	Flames obscured
8:12	Second sprinkler activation
8:30	Curtains in flames
9:25	Complete back side of vinyl chair in flames
9:50	Fire in back of vinyl chair; sprinkler has extinguished fire at curtains; 1/4 of curtains toward west wall remain
10:20	Fire diminishing in back of vinyl chair
10:45	Small fire left side of arm rest; small fire bottom rear of vinyl chair
12:00	Small fire persisting in back of vinyl chair
12:35	Dense smoke throughout room; no sign of fire

TABLE A-3 (Continued)

Post-Test Fire Damage Assessment

Vinyl Chair:	75% consumed by fire
Sofa:	Herculon covering on right side melted
Curtains:	Consumed on northeast side (behind vinyl chair)
End Table:	Under part slightly charred
Carpet:	1-ft dia hole burned through directly under wastebasket
Wood Paneling:	Slightly charred behind vinyl chair

a) 30 sec before sprinkler activation
ΔT_g = 99°F

b) 20 sec before sprinkler activation
ΔT_g = 128°F

c) 10 sec before sprinkler activation
ΔT_g = 153°F

d) sprinkler activation
ΔT_g = 292°F

$\Delta T_g = T_g - T_{go}$
T_g = gas temperature adjacent to sprinkler No. 1
T_{go} = initial gas temperature adjacent to sprinkler No. 1; = 94°F

FIGURE A.3 PICTORIAL HISTORY OF FIRE TEST S1.3

TABLE A-4

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S2.1

Time (min:sec)	Observations
0:00	Ignition
0:10	Visible fire in wastebasket
0:35	Very light smoke from wastebasket
0:55	Wastebasket melting
1:22	Wastebasket tipping over toward vinyl chair
2:00	Very light smoke in upper half of room
2:22	Small carpet fire around wastebasket
2:30	Vinyl chair smoldering
4:00	Left side of vinyl chair igniting
4:15	Medium smoke throughout room
4:30	Flames at left side of vinyl chair creeping up left side of back rest
5:10	Curtains at northeast side igniting
5:15	Dense smoke throughout room
5:20	Sofa right side burst into flames
5:23	Sprinkler activation
5:34	2nd sprinkler activation
7:25	Observation made outside; dense black smoke observed from windows; vinyl chair and sofa burning

Post-Test Fire Damage Assessment

Vinyl Chair:	90% consumed by fire
Sofa:	Herculon covering on right side melted; padding burned exposing heavily charred wood frame; herculon fabric melted on seat cushions
Curtains:	Completely consumed
End Table:	Completely consumed by fire
Carpet:	2-ft dia hole burned through directly under wastebasket

a) 20 sec before sprinkler activation
ΔTg = 98°F

b) 10 sec before sprinkler activation
ΔTg = 188°F

c) 5 sec before sprinkler activation
ΔTg = 275°F

d) sprinkler activation
ΔTg = 451°F

ΔTg = Tg - Tgo
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 69°F

FIGURE A.4 PICTORIAL HISTORY OF FIRE TEST S2.1

TABLE A-5

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S2.2

Time (min:sec)	Observations
0:00	Ignition
0:10	Visible fire in wastebasket
0:30	Light smoke from wastebasket
1:00	Wastebasket melting
1:17	Wastebasket tipping over toward vinyl chair
1:45	Small carpet fire around wastebasket
1:50	Bottom back left side of vinyl chair burning
2:10	Light smoke upper half of room
3:15	Fire increasing left side vinyl chair
4:10	Fire progressing up back rest and left side of vinyl chair
5:00	Black smoke coming from vinyl chair
5:30	Medium smoke throughout room
6:20	Left side vinyl chair completely involved in flames
6:45	Curtains on northeast side igniting; flames at ceiling level
7:05	Sprinkler activation
7:10	Back and left side of vinyl chair in flames; curtains burning behind vinyl chair; sofa on right side smoldering
7:25	2nd sprinkler activation
7:28	Sofa right side burst into flames
7:45	Fire under, in back of, and on left side of vinyl chair; sofa burning right side; curtains burning behind vinyl chair
8:25	Dense smoke throughout room
8:30	Flames in back rest and left side of vinyl chair and increasing; fire still burning right side of sofa
8:45	Fire from vinyl chair at ceiling height
9:30	Dense smoke throughout room
10:15	Vinyl chair and sofa involved in fire and decreasing
10:30	Dense smoke throughout room

Post-Test Fire Damage Assessment

Vinyl Chair:	90% consumed
Curtains:	Consumed along northeast wall; along northwest wall melted along curtain rod and fell to floor
Carpet:	3-ft dia hole burned through directly under wastebasket
Sofa:	Herculon covering on right side burned exposing padding and wood frame

a) 20 sec before sprinkler activation
ΔTg = 130°F

b) 10 sec before sprinkler activation
ΔTg = 272°F

c) 5 sec before sprinkler activation
ΔTg = 373°F

d) sprinkler activation
ΔTg = 472°F

ΔTg = Tg - Tgo
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 76°F

FIGURE A.5 PICTORIAL HISTORY OF FIRE TEST S2.2

TABLE A-6

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - Test S2.3

Time (min:sec)	Observations
0:00	Ignition
0:12	Visible fire in wastebasket
0:30	Very light smoke from wastebasket
0:35	Wastebasket melting
1:15	Wastebasket tipping over toward vinyl chair
1:40	Bottom left side vinyl chair burning
2:00	Fire at arm rest level in vinyl chair
2:10	Flames decreasing in vinyl chair
2:30	Small carpet fire around wastebasket
3:00	Fire increasing in vinyl chair
3:30	Flames completely involved in left side of vinyl chair
4:00	Medium smoke throughout room
4:15	Dense smoke from vinyl chair
4:16	Curtains on northeast wall igniting; flames at ceiling level
4:17	Sprinkler activation
4:38	2nd sprinkler activation
4:50	Back and left side of vinyl chair involved in flames
5:00	Fabric right side of sofa melting
5:15	Fire contained to vinyl chair
5:20	Sofa right side smoldering
6:15	Fire increasing in vinyl chair
6:30	Fire burning vinyl chair from back to front
7:00	50% of back rest in vinyl chair burned away
7:15	Dense smoke throughout room
7:30	Fire decreasing in vinyl chair
8:30	Complete back rest of chair has burned
8:45	Flames in vinyl chair 3 ft high and decreasing
9:00	Fire contained to under part of vinyl chair; dense (steam-like) smoke
10:30	Small fire under vinyl chair
11:00	Dense (steam-like) smoke
12:00	Curtains northwest wall still intact
14:00	Small fire under vinyl chair
17:00	Medium to heavy (steam-like) smoke; small fire under vinyl chair

Post-Test Fire Damage Assessment

Vinyl Chair:	75% consumed
Curtains:	Curtains on northeast wall fell to floor where water from sprinkler extinguished their flames
End Table:	Slightly charred
Sofa:	Herculon covering on right side melted, exposing padding
Carpet:	2-ft dia hole burned through directly under wastebasket

a) 20 sec before sprinkler activation
$\Delta Tg = 66°F$

b) 10 sec before sprinkler activation
$\Delta Tg = 83°F$

c) 5 sec before sprinkler activation
$\Delta Tg = 95°F$

d) sprinkler activation
$\Delta Tg = 125°F$

ΔTg = Tg - Tgo
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 77°F

FIGURE A.6 PICTORIAL HISTORY OF FIRE TEST S2.3

TABLE A-7

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S3.1

Time (min:sec)	Observations
0:00	Ignition
0:20	Visible fire in wastebasket
0:40	Very light smoke from wastebasket
0:50	Wastebasket melting
1:15	Wastebasket tipped over toward vinyl chair
1:30	Very light smoke in upper half of room
3:00	Very light smoke throughout room
4:00	Flames progressing up left side of vinyl chair toward back
5:20	Small carpet fire under wastebasket
5:45	Small fire inside 1.5-ft dia hole in left side of vinyl chair; progressing forward
6:30	Fire increasing on left side of vinyl chair
6:45	Left side of vinyl chair completely involved in flames
7:15	Curtains northeast side igniting
7:30	Left and back side of vinyl chair, curtains on northeast side of room completely involved in flames
7:41	Right side of sofa igniting
7:45	1st sprinkler activation
8:00	Curtains northwest side ignited; 2nd sprinkler activation
8:10	Flames increasing along ceiling surface over ignition area and north wall
8:15	Ceiling flames coming down toward west wall
8:30	Right side of sofa involved in flames
8:45	Vinyl chair, curtains, right side of sofa, end table, paneling above window and ceiling involved in flames
8:50	Curtains northwest side falling to floor
9:00	Dense smoke throughout room
9:20	Ceiling completely involved and flames coming down west wall

Post-Test Fire Damage Assessment

Vinyl Chair:	90% consumed
Curtains:	Consumed
End Table:	Consumed
Sofa:	Herculon covering on right side melted; padding burned exposing wood frame which was heavily charred
Carpet:	2-ft dia hole burned through directly under wastebasket
Wood Paneling:	Consumed directly behind vinyl chair exposing heavily charred wood studs

a) 20 sec before sprinkler activation
$\Delta Tg = 142°F$

b) 10 sec before sprinkler activation
$\Delta Tg = 215°F$

c) 5 sec before sprinkler activation
$\Delta Tg = 277°F$

d) sprinkler activation
$\Delta Tg = 470°F$

$\Delta Tg = Tg - Tgo$
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 70°F

FIGURE A.7 PICTORIAL HISTORY OF FIRE TEST S3.1

TABLE A-8

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S3.2

Time (min:sec)	Observations
0:00	Ignition
0:10	Visible fire in wastebasket
0:35	Very light smoke
1:40	Wastebasket tipping toward vinyl chair
1:50	Light smoke throughout room
2:00	Flames increasing on left side of vinyl chair
2:30	Flames completely involved on left side of vinyl chair
2:48	Curtains on northeast side igniting
3:00	Fire from curtains at ceiling level
3:01	Sprinkler activation
3:20	Portion of curtains on northeast side remain on curtain rod, while other portion fallen behind and on top of vinyl chair
3:45	Portion of curtain on curtain rod burning; ceiling tile over chair ignited
4:00	Flames on left side and behind vinyl chair, small fire in paneling above northeast window and small ceiling fire
4:19	2nd sprinkler activation
4:20	Flames increasing left side and behind vinyl chair
4:45	Flames in paneling behind and above vinyl chair, on ceiling above ignition, and end table involved
5:00	Ceiling along north wall, paneling behind chair and curtains on northwest side involved in flames
5:25	East wall paneling ignited and spreading
5:35	Fire throughout ceiling area
6:00	Medium smoke throughout room
6:15	Vinyl chair completely involved in flames
7:20	East wall along top burning and fire spreading to south end of room
8:20	Flames from ceiling coming down west wall
9:00	Medium smoke throughout room
10:30	Paneling above windows and 2 in. x 4 in. studs burning
11:30	Most of vinyl chair consumed, 2 x 4 studs in northeast corner, paneling along top of east wall burning

TABLE A-8 (Continued)

Post-Test Fire Damage Assessment

Vinyl Chair:	90% consumed
Curtains:	Consumed along north wall
End Table:	Consumed
Sofa:	Herculon covering on right side melted; padding burned exposing heavily charred wood frame
Carpet:	3-ft dia hole burned through directly under wastebasket
Ceiling:	Most ceiling tiles burned or charred
Wood Paneling:	Directly behind vinyl chair, above north window, along top of east wall consumed, exposing heavily charred wood studs

a) 20 sec before sprinkler activation
$\Delta Tg = 37°$

b) 10 sec before sprinkler activation
$\Delta Tg = 65°$

c) 5 sec before sprinkler activation
$\Delta Tg = 83°F$

d) sprinkler activation
$\Delta Tg = 169°F$

ΔTg = Tg - Tgo
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 63°F

FIGURE A.8 PICTORIAL HISTORY OF FIRE TEST S3.2

TABLE A-9

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S3.3

Time (min:sec)	Observations
0:00	Ignition
0:20	Visible fire in wastebasket
0:30	Wastebasket melting
0:52	Wastebasket tipped toward vinyl chair
1:28	Bottom left side of vinyl chair ignited
2:00	Light smoke in upper half of room
3:30	Flames on left side of vinyl chair at arm rest level
3:58	Flames completely involving left side of vinyl chair
4:17	Curtains on northeast side ignited
4:20	Sprinkler activation
4:30	Right side of sofa smoldering
4:50	Flames contained to left side and in back of vinyl chair
4:52	2nd sprinkler activation
5:10	Flames decreasing in vinyl chair
5:20	Medium to dense white (steam-like) smoke
5:35	Fabric along curtain rod ignited
6:00	Curtains on northeast wall fallen to floor
6:25	Fire contained to vinyl chair and fabric along curtain rod
7:00	Dense white (steam-like) smoke throughout room
8:00	Fire out along curtain rod
8:20	Flames increasing in back of vinyl chair
9:00	Flames in back rest of vinyl chair at 5-ft level
10:00	Flames contained in vinyl chair at 5.5-ft level
11:30	Medium to dense white (steam-like) smoke
12:00	Small carpet fire behind vinyl chair
12:30	Flames in vinyl chair increasing to 6-ft level
13:00	Most of back rest of vinyl chair consumed by fire
14:00	Medium to dense smoke throughout room; flames at vinyl chair decreasing to 5-ft level
15:30	Flames contained to vinyl chair
16:30	Flames decreasing to 3-ft level
17:30	Medium smoke throughout room
18:00	Flames decreasing to 2-ft level
20:00	Small fire under seat of vinyl chair

Post-Test Fire Damage Assessment

Vinyl Chair:	75% consumed
Curtains:	Burned and fell from northeast half
Carpet:	1-ft dia hole burned through directly under wastebasket

a) 20 sec before sprinkler activation
ΔTg = 74°F

b) 10 sec before sprinkler activation
ΔTg = 91°F

c) 5 sec before sprinkler activation
ΔTg = 97°F

d) sprinkler activation
ΔTg = 116°F

ΔTg = Tg - Tgo
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 67°F

FIGURE A.9 PICTORIAL HISTORY OF FIRE TEST S3.3

TABLE A-10

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S3.4

Time (min:sec)	Observations
0:00	Ignition
0:20	Visible fire in wastebasket
0:30	Wastebasket melting
1:00	Wastebasket tipping toward vinyl chair
1:30	Light smoke from wastebasket
2:30	Vinyl chair bottom left side ignited
3:00	Light smoke upper half of room
4:50	Flames on left side of vinyl chair, at arm rest level
5:40	Left side vinyl chair completely involved
6:20	Curtains on northeast wall igniting
6:24	Flames to ceiling level
6:25	Sprinkler activation
6:35	2nd sprinkler activation
6:38	Curtains on northeast wall falling to floor directly behind vinyl chair
6:48	Fire contained to vinyl chair and fabric along curtain rod above northeast window
6:50	Right side of sofa smoldering
7:30	Fire out in fabric above window; flames contained to back and left side of vinyl chair
7:45	Flames decreasing in vinyl chair
8:00	Flames increasing in back of vinyl chair to 5-ft level
9:30	Flames contained to back of vinyl chair still at 5-ft level
10:00	Flames decreasing in vinyl chair to 4-ft level
11:00	Flames at 3-ft level
12:40	Flames at 2-ft level
13:50	Small fire under seat of vinyl chair

Post-Test Fire Damage Assessment

Vinyl Chair:	75% consumed
Curtains:	Northeast section had fallen to floor; water from sprinkler extinguished fire; curtains on northwest section melted along curtain rod but did not fall
Carpet:	2-ft dia hole burned through directly under wastebasket
Sofa:	Fabric melted exposing padding on right side
End Table:	Heavily charred

a) 20 sec before sprinkler activation
ΔTg = 65°F

b) 10 sec before sprinkler activation
ΔTg = 97°F

c) 5 sec before sprinkler activation
ΔTg = 115°F

d) sprinkler activation
ΔTg = 184°F

ΔTg = Tg - Tgo
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 69°F

FIGURE A.10 PICTORIAL HISTORY OF FIRE TEST S3.4

TABLE A-11

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S3.5

Time (min:sec)	Observations
0:00	Ignition
0:35	Visible fire in wastebasket
0:45	Wastebasket melting
1:22	Light smoke from wastebasket
1:55	Wastebasket tipping toward vinyl chair
7:00	Light smoke throughout room
11:00	Flames on left side vinyl chair, at arm rest level
11:30	Left side vinyl chair completely involved
11:44	Curtains on northeast wall involved in flames
11:46	Sprinkler activation
12:08	2nd sprinkler activation
13:00	Fire contained to vinyl chair and curtains on northeast wall
13:05	Curtains on northeast wall fell to floor and still burning
13:17	Ceiling fire started in northeast corner spreading along top north wall
13:28	Right side of sofa involved in flames
14:00	Flames in back and left side of vinyl chair
14:02	Flames at ceiling along north wall and wood paneling above window; flames spreading to top of east wall; right side of sofa burning
14:03	Curtains on northwest side fallen to floor still burning behind vinyl chair
14:30	Flames decreasing throughout room
14:40	Ceiling fire out
15:30	Medium to dense white (steam-like) smoke throughout room
15:40	Flames contained to vinyl chair
15:50	Dense white (steam-like) smoke throughout room

Post-Test Fire Damage Assessment

Vinyl Chair:	75% consumed
Curtains:	Northeast section was completely consumed; northwest section burned at curtain rod and fell to floor
Carpet:	3-ft dia hole burned through directly under wastebasket
Sofa:	Fabric melted exposing padding and wood frame on right side
End Table:	Heavily charred
Wood Paneling:	Consumed above north window exposing charred wood 2 x 4 studs

TABLE A-12

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S3.6

Time (min:sec)	Observation
0:00	Ignition
0:15	Visible fire in wastebasket
0:30	Light smoke from wastebasket
0:40	Wastebasket melting
1:30	Wastebasket tipping toward vinyl chair
1:45	Vinyl chair ignited on bottom left side
3:00	Flames on left side of vinyl chair at arm rest level
4:15	Left side of vinyl chair completely involved in flames
4:23	Curtains on northeast side ignited
4:28	Sprinkler activation
4:45	Light smoke throughout room
5:00	Fire out on northeast curtains
5:15	Fire contained to left side and back side of vinyl chair
6:00	Light smoke throughout room
6:30	Fire contained to back of vinyl chair, flames at 5-ft level
7:35	Flames increasing in back of vinyl chair to 6-ft level
10:00	Flames still at 6-ft level, light to medium smoke
11:00	Flames increasing to 7-ft level, curtains on northeast side starting to burn again
12:00	Northeast curtains fell to floor
13:00	Flames decreasing in back of vinyl chair to 5-ft level
14:50	Flames decreasing to 3-ft level in back of vinyl chair
15:00	Medium smoke throughout room
15:30	Small fire in vinyl chair

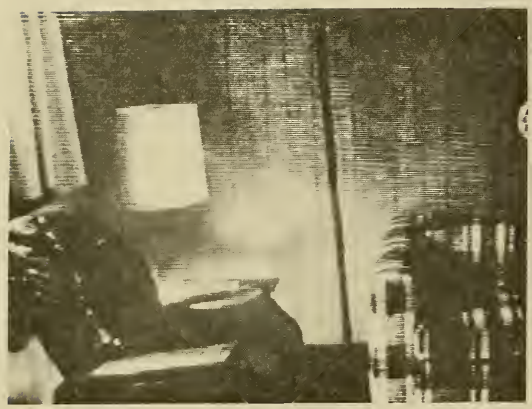
Post-Test Fire Damage Assessment

Vinyl chair: 50% consumed

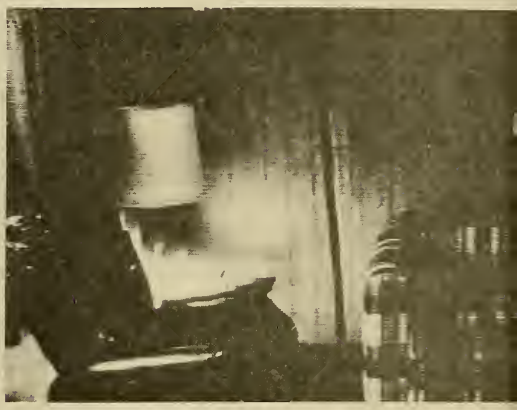
Curtains: Burned along top northeast section

Carpet: 1-ft dia hole burned through directly under wastebasket

Wood Paneling: Charred 4 in. wide by 1 ft long directly behind vinyl chair



a) 20 sec before sprinkler activation
ΔT_g = 63°F



b) 10 sec before sprinkler activation
ΔT_g = 73°F

c) 5 sec before sprinkler activation
ΔT_g = 96°F

d) sprinkler activation
ΔT_g = 125°F

$\Delta T_g = T_g - T_{go}$
T_g = gas temperature adjacent to sprinkler No. 1
T_{go} = initial gas temperature adjacent to sprinkler No. 1; = 71°F

FIGURE A.11 PICTORIAL HISTORY OF FIRE TEST S3.6

TABLE A-13

OBSERVATIONS AND POST-TEST DAMAGE ASSESSMENT - TEST S3.7

Time (min:sec)	Observations
0:00	Ignition
0:30	Visible fire in wastebasket
1:05	Wastebasket melting
1:30	Light smoke from wastebasket
2:26	Wastebasket tipped toward vinyl chair
3:00	Bottom left side of vinyl chair ignited
4:40	Light smoke throughout room
5:00	Small fire under end table and near vinyl chair
6:00	Flames on bottom left side of vinyl chair
7:00	Flames on left side of vinyl chair at arm rest level
7:30	Left side of vinyl chair completely involved in flames
7:32	Sprinkler activation
8:30	Fire contained to left side of chair
9:00	Fire progressing around to back side of chair, flames at 5-ft level
9:30	Fire on the chair has decreased to 4-ft level
10:30	Fire contained to left side and back rest of vinyl chair at 4-ft level
11:00	Fire increased to 5-ft level
11:30	Medium to dense smoke
14:00	Fire contained to vinyl chair at 5-ft level
15:00	Fire increased to 6-ft level
15:30	Fire increased to 6.5-ft level
16:00	Medium to dense smoke
16:30	Flames hitting ceiling
17:00	Back rest of vinyl chair burned away; flames decreasing
17:30	Fire contained under seat of vinyl chair
18:00	Dense smoke
19:00	Small fire under seat of vinyl chair
20:00	Dense smoke throughout room
21:00	Smoke starting to clear

Post-Test Fire Damage Assessment

Vinyl Chair:	75% consumed
Carpet:	2-ft dia hole burned through directly under wastebasket
End Table:	Slightly charred

a) 20 sec before sprinkler activation
$\Delta Tg = 58°F$

b) 10 sec before sprinkler activation
$\Delta Tg = 65°F$

c) 5 sec before sprinkler activation
$\Delta Tg = 76°F$

d) sprinkler activation
$\Delta Tg = 89°F$

ΔTg = Tg - Tgo
Tg = gas temperature adjacent to sprinkler No. 1
Tgo = initial gas temperature adjacent to sprinkler No. 1; = 76°F

FIGURE A.12 PICTORIAL HISTORY OF FIRE TEST S3.7

a) Test S1.1

b) Test S1.2

c) Test S1.3

FIGURE A.13 POST-TEST APPEARANCE OF TESTS S1.1, S1.2, S1.3, S2.2, S3.3, S3.6

a) Test S2.2

b) Test S3.3

c) Test S3.6

FIGURE A.13 POST-TEST APPEARANCE OF TESTS S1.1, S1.2, S1.3, S2.2, S3.3, S3.6 (Continued)

APPENDIX B

SPRINKLER LINK RESPONSE TIMES

The hot combustion gases generated from a fire in a room first impinge on the ceiling and then spread underneath the ceiling. A sprinkler link mounted at the ceiling exposed to the gas flow underneath the ceiling is assumed to be heated primarily by forced convection. The governing equation for the temperature response of a sprinkler link can be expressed as:

$$mc\ (d\ T_r/dt) = h_c\ A\ (T_g - T_r) \tag{B.1}$$

with the initial condition t=0, $T_r = T_g = T_{go}$

where:

- m = mass of link;
- c = specific heat of link;
- h_c = convective heat-transfer coefficient;
- A = surface area of link;
- T_r = link temperature;
- T_g = gas temperature;
- t = time.

Equation (B.1) can also be written as:

$$dT_r/dt = \tau^{-1}\ (T_g - T_r) \tag{B.2}$$

where: $\tau = mc/(h_c A)$. The quantity, τ, has dimensions of time and is referred to as the sprinkler link time constant.

A "plunge test" has been proposed for obtaining the time constants of sprinkler links[7]. In a plunge test, the test sprinkler is suddenly immersed in an air flow of constant temperature and velocity. A large number of plunge tests were conducted by Heskestad and Smith[7] for 10 different sprinkler models representative of the current market. Gas temperatures were varied from 260° to 800°F and gas velocities were varied within the range of 5 to 17 ft/s. It was found[7] that the product, $\tau u^{1/2}$ was relatively insensitive to gas temperature

and gas velocity. Hence, if the time constant, τ_o, is known for a given velocity, u_o, the value, τ, at the arbitrary velocity, u, is given by

$$\tau = \tau_o \, (u_o/u)^{1/2} \quad . \tag{B.3}$$

Substituting eq (B.3) into eq (B.2), eq (B.2) becomes:

$$dT_r/dt = (\tau_o u_o^{1/2})^{-1} \, u^{1/2} \, (T_g - T_r) \quad . \tag{B.4}$$

With the aid of the gas temperature history, $T_g(t)$, and the gas velocity history, u(t), in the vicinity of the sprinkler, the thermal response of a sprinkler link with a known time constant, τ_o (at a reference gas velocity, u_o) can be predicted by using eq (B.4). The solution of eq (B.4), $T_r(t)$, can be obtained numerically by using the fourth-order Runge-Kutta scheme.

In all the fire tests, the gas temperature and the gas velocity in the vicinity of the sprinkler closest to the fire source were measured. The time constants of the sprinkler links and the simulated links employed in the program were obtained in a prototype plunge-test tunnel[7] with a velocity of 7.44 ft/sec.

The time constants of the commercially available sprinkler link and the manufacturer's prototype link were measured at three sprinkler orientations relative to the air flow direction: 1) the plane of the sprinkler supporting arms parallel to the flow direction; 2) the plane of the sprinkler supporting arms perpendicular to the flow direction with the link in front of the plane; and 3) the plane of the sprinkler supporting arms perpendicular to the flow direction with the link behind the plane. The ratios of the maximum time constant over the minimum time constant of the commercial link and the manufacturer's link are 1.12 and 1.21 respectively. In a real fire situation a ceiling-mounted sprinkler would be exposed to a highly turbulent ceiling flow, with the instantaneous flow direction varying over a wide angular band. It is expected that the sensitivity of the sprinkler links time constant relative to the general flow direction in a ceiling flow generated by fire is considerably smaller than that in the plunge-test tunnel[7]. Hence, in solving eq (B.4) to obtain the link thermal response for Tests S1.3, S2.1, S2.2 and S2.3 with the commercial link, only the average value of the time constants measured at the three sprinkler

orientations was used. The time constants of the commercial link and the manufacturer's prototype link reported in Tables I, II and III are also the averaged values.

For the simulated links (brass sensing disks) of three different thicknesses, the time constants were measured at only a single disk orientation with the front surface of the disk facing upstream of the air flow. These measured values are reported in Section 3.3.2.

The computed values of sprinkler link temperature at the time of sprinkler activation for Tests S1.3, S2.1, S2.2 and S3.1 are listed in Table B.1. The computed values are quite close to the link temperature rating, 165°F except for Test S2.2. Figure B.1 shows the computed and measured temperatures of the three simulated links of different time constants, adjacent to Sprinkler No. 1 for Test S3.3. The agreement between the computed and the measured values is quite good. It has been demonstrated that the thermal response of a sprinkler link with known time constant exposed to ceiling flow generated by fire can be predicted rather accurately with the aid of the gas temperature and the gas velocity measurements in the vicinity of the sprinkler.

TABLE B.1

COMPUTED VALUES OF SPRINKLER LINK TEMPERATURES AT THE TIME OF SPRINKLER ACTIVATION FOR TESTS S1.3, S2.1, S2.2 AND S3.1

Test	S1.3	S2.1	S2.2	S3.1
T_r (°F)	163	161	190	167
t_s (sec)	439	323	425	465

Note: T_r - computed sprinkler link temperature
t_s - measured sprinkler response time

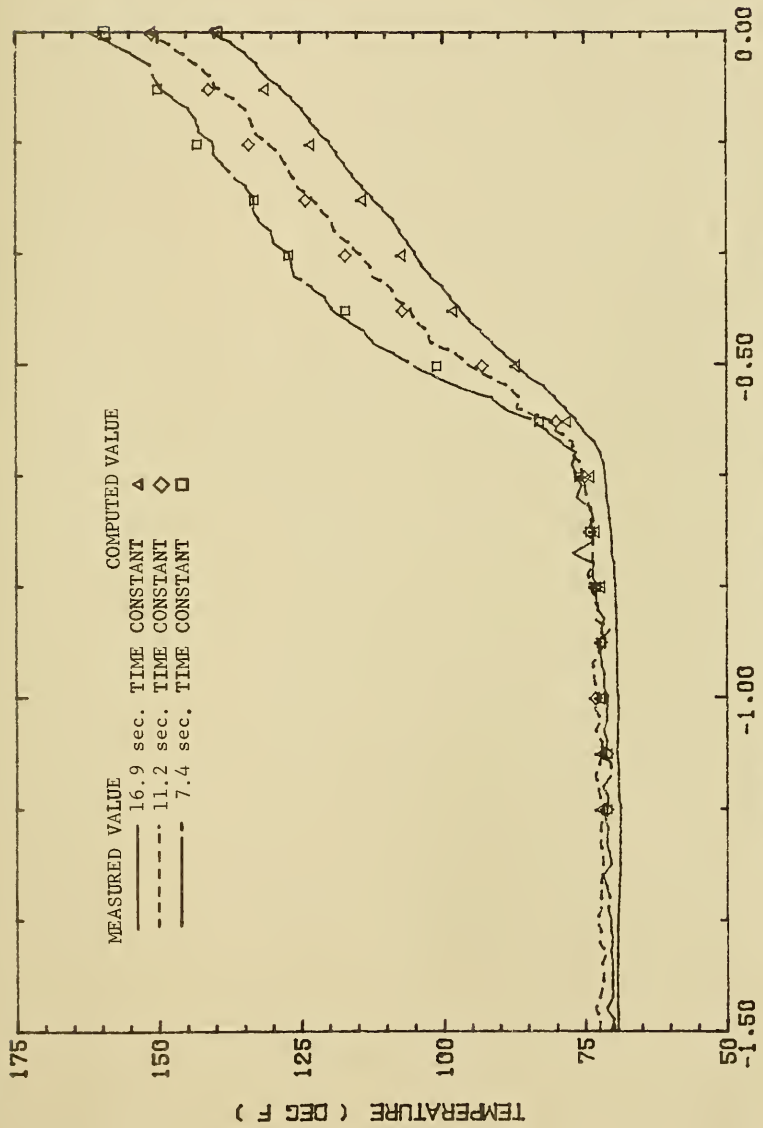


FIGURE B.1 COMPUTED AND MEASURED TEMPERATURES OF THREE SIMULATED LINKS OF DIFFERENT TIME CONSTANTS, ADJACENT TO SPRINKLER NO.1 FOR TEST S3.3

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